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Superconducting Matching Networks in Monopole Antennas

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Westinghouse Electronic Systems Group
Baltimore, MD 21203

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FOREWORD

This Final Technical Report covers work performed by Westinghouse Electric Corporation at the Westinghouse Electronic Systems Group, Baltimore, Md. 21203 and at the Science and Technology Center, Pittsburgh, Pa. 15235 under Contract No. N00014-89-C-0180. The effort was sponsored by Office of Naval Research.

The work reported here was performed during the period 1 August, 1989 to 31 July 1991 under the direction of Mr. Jon Moellers, Project Manager. Dr. Y. S. Park was the Navy Program Manager.

INTRODUCTION

The goals of this program were to demonstrate the performance advantages of UHF Super Directive Array using a monopole antenna matching network made of high temperature superconducting (HTS) material over a monopole antenna matching network made of gold and to demonstrate the feasibility of using HTS material matching networks to feed a two element electrically small superdirective monopole array. In both cases only the matching networks were made of HTS material. The radiators were made of silver, copper, and steel. The electrically small monopole antenna and the electrically small element monopole antenna array were operated in the UHF band because the need exists for a high efficiency electrically small array operating in the UHF range as part of a multispectral seeker of an air-to-air missile. To date no antenna system consisting of electrically small conventional metal monopole radiators and HTS material matching networks has been demonstrated.

An electrically small superdirective monopole array with superconducting matching networks is a candidate for use in an air-to-air missile as part of a multispectral seeker. The seeker must have a multispectral capability in order to successfully engage advanced Low Observable aircraft and missiles. The air-to-air missile guidance is initially provided by a surveillance and control aircraft. The surveillance and control aircraft also provides target tracking and mid course updating. As the missile approaches a target the multispectral seeker of the missile provides target acquisition and terminal tracking and guidance. The multispectral seeker operates in four frequency bands; UHF, X, Ku, and IR. As the multispectral seeker begins target acquisition, it operates in the UHF mode. Compared to X band and IR, UHF provides greater detection capability against stealthy vehicles approximately the size of cruise missiles. Its resolution however, is the coarsest. As the seeker comes closer to the target finer target resolution is provided by the X and Ku band radar. Terminal tracking is provided by the IR sensor.

Prior to the design and building of the monopole antenna systems a number of tasks were to be accomplished, (1) a study of HTS UHF antenna concepts (monopole, dipole, and loop antennas) was to be completed, (2). the HTS materials were characterized and HTS material processing was improved, (3) a method was devised for integrating the HTS matching network into an antenna system, and (4) techniques were to be developed for accurately measuring the gain of the antennas. After completion of tasks (1) through (4) the matching networks were designed and built.

Experimental results showed that the monopole antenna fed by an HTS matching network had a gain approximately 2 dB greater than an identical monopole antenna fed by a gold matching network. Experimental results for the two element monopole array with superconducting matching networks showed an acceptable pattern.

Rather than build a two element antenna array, the initial goal was to build a four element antenna array and associated matching networks. A budget cutback forced us to build a two element antenna array and associated matching network.

During the course of this program high-temperature superconducting (HTS) $YBa_2Cu_3O_7$ (YBCO) film growth and device fabrication techniques evolved considerably, improving the state of the art and the quality of the tested devices. We went from low yield single sided YBCO films using silver paint to attach the substrates to the sputtering chamber heating block, to state of the art double-sided 2-inch diameter wafers coated on both sides. With respect to fabrication, we progressed from photolithography on small substrates of rectangular shape, with its concomitant lack of pattern definition precision at the edges, to full wafer processing; from wet etching, which was high risk and degraded the pattern definition, to ion milling, which produced clear patterns.

These developments were not straightforward to implement and, at the end of the program, were not 100% reliable, as will be seen in later sections of this report. These developments represent, however, significant progress towards the establishment of electrically small UHF Super Directive Array technology.

FINAL REPORT

DESIGN

For both the monopole antenna and the two element antenna array the antenna element network consisted of a microstrip transmission line, a single stub matching network, and the monopole antenna (see figures 1 and 2).

The single, parallel stub matching network was selected in order to keep the microstrip matching network simple and relatively compact. The microstrip implementation required neither vias nor air bridges.

The monopole antenna admittance was determined from ESP a moment method surface patch code developed at the Electro-Science Laboratory at Ohio State University by Dr. Edward H. Newman. ESP uses a piecewise sinusoidal reaction formulation. The monopole antenna impedance for a 3.3 cm long monopole antenna with a .91 mm diameter operating at a frequency of 800 MHz and embedded in a 50 cm x 50 cm ground plane was determined to be 3.1 - j 327 ohms.

The matching network was modelled on Touchstone, a commercial circuit analysis software package (Touchstone is an EEsof trademark). In order to model the power radiated by the monopole, the Touchstone file was a two port circuit (see figure 3) which was terminated at port 1, the source end, with a standard 50 ohm termination, and at port 2, the monopole end, with a 3.1 - j 327 ohm termination.

The real port of the monopole termination, 3.1 ohms, represented the antenna element radiation resistance and ohmic losses. Using ESP, we determined that the monopole was approximately 99% efficient. The monopole reactance was modelled as a lumped capacitor. Thus $|S_{21}|^2$ approximately represented the monopole's radiated power. The Touchstone file also included the effects of the coaxial monopole feed, the Wiltron k-connector that connected the coaxial feed to the microstrip line, the dielectrics' permittivities and loss tangents, the model of the T-junction connecting the microstrip transmission line with the parallel stub, and the stub's end effects. The microstrip

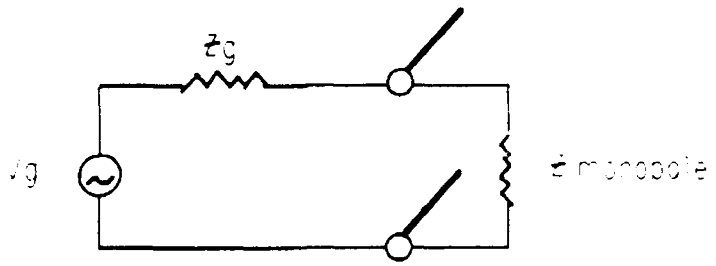


FIGURE 1. THE TRANSMISSION LINE CONCEPT FOR THE ANTENNA MATCHING NETWORK. THE SINGLE STUB MATCHING NETWORK IS ONE QUARTER WAVELENGTH FROM THE MONOPOLE ANTENNA.

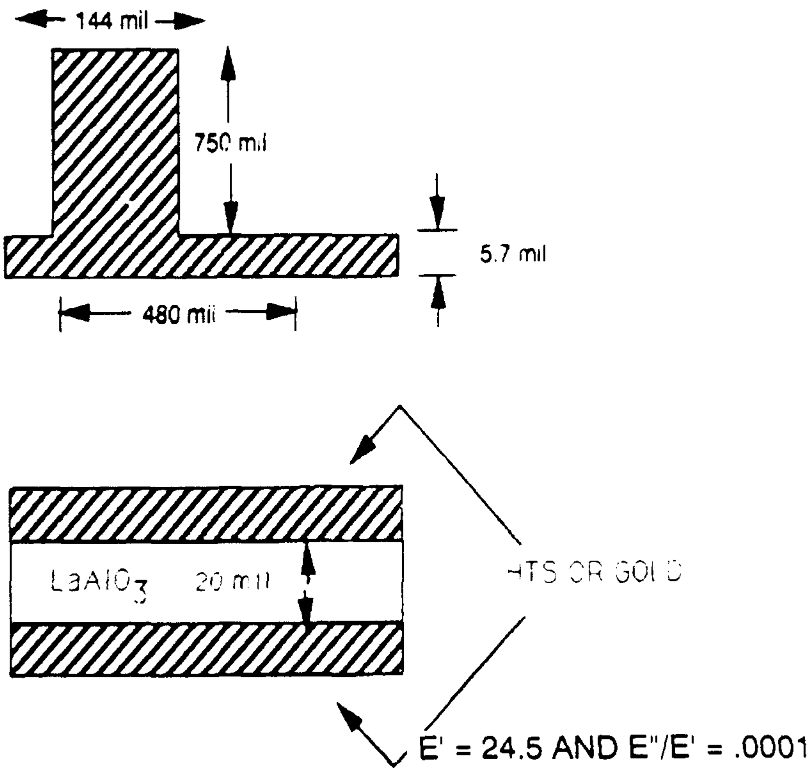


FIGURE 2. MICROSTRIP IMPLEMENTATION OF THE TRANSMISSION LINE CONCEPT FOR THE ANTENNA MATCHING NETWORK FOR EITHER HTS OR GOLD. THE DIELECTRIC CONSTANT OF THE $LaAlO_3$ SUBSTRATE IS: E' = 24.5 AND E"/E' = .0001

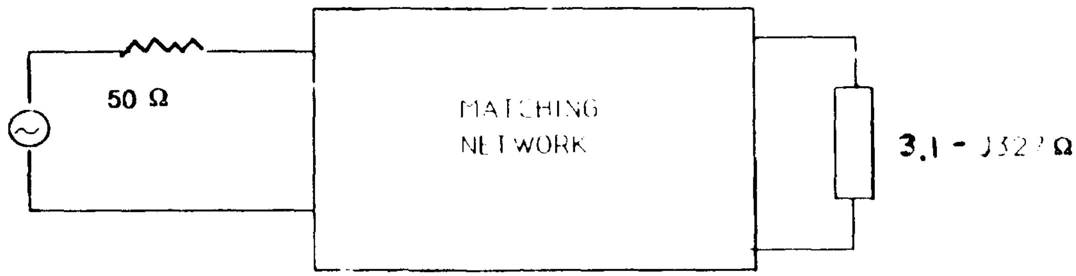


FIGURE 3. SCHEMATIC OF A TOUCHSTONE FILE USED TO DETERMINE THE OPTIMUM PARAMETERS OF A SINGLE STUB MATCHING NETWORK FOR A 3.3 CM LONG MONOPOLE ANTENNA WITH A .91 MM DIAMETER OPERATING AT A FREQUENCY OF 800 MHZ AND EMBEDDED IN A 50CM X 50CM GROUND PLANE.

substrate material was assumed to have a dielectric constant of 24.5 and a loss tangent of .0001. Figure 4 is a plot of the gain improvement (dB) as a function of monopole length of a monopole antenna with an HTS matching network compared to a gold matching network. The frequency of operation was 800 Mhz. The monopole impedances at each length were calculated using ESP. The matching networks were optimized using Touchstone. The smaller the monopole antenna, the greater the mismatch the antenna presented to the 50 ohm transmission line, hence the greater the benefit of HTS over gold. This result was similar to results previously reported for a dipole antenna by Dr. R. Dinger of the Naval Weapons Center, China Lake[1].

Figure 5 is a plot of the antenna bandwidths for both HTS and gold as a function of antenna height for a center frequency of 800 MHz and monopole diameter of .91 mm. The bandwidth of HTS can be substantially improved by the use of more elaborate matching networks.

In order to assess the accuracy of the computer code ESP, the computer code predicted impedance was compared to impedance measurements made on an HP 8510 ANA. Figure 6 is a plot of the ESP calculated and ANA measured real part of the impedance as a function of monopole length. Figure 7 is a plot of the ESP calculated and ANA measured imaginary part of the impedance as a function of monopole length. ESP correctly predicted the trend of the real part of the impedance and gave quite close agreement with the measured imaginary part of the impedance. The reason there was not closer agreement between ESP and the ANA measured real part of the impedance was due to the small magnitude of the real part of the impedance compared to the magnitude of the imaginary part.

In order to design an endfire array of electrically small antenna elements embedded in an electrically large (approximately 1 wavelength at the operating frequency of 800 MHz) ground plane, the magnitudes and phases of the antenna elements' currents had to be determined. ESP was used to determine the impedance matrix of the antenna elements from which the correct voltage excitation for endfire radiation could be determined. Figure 8 is a schematic of two antennas radiating. The active impedances

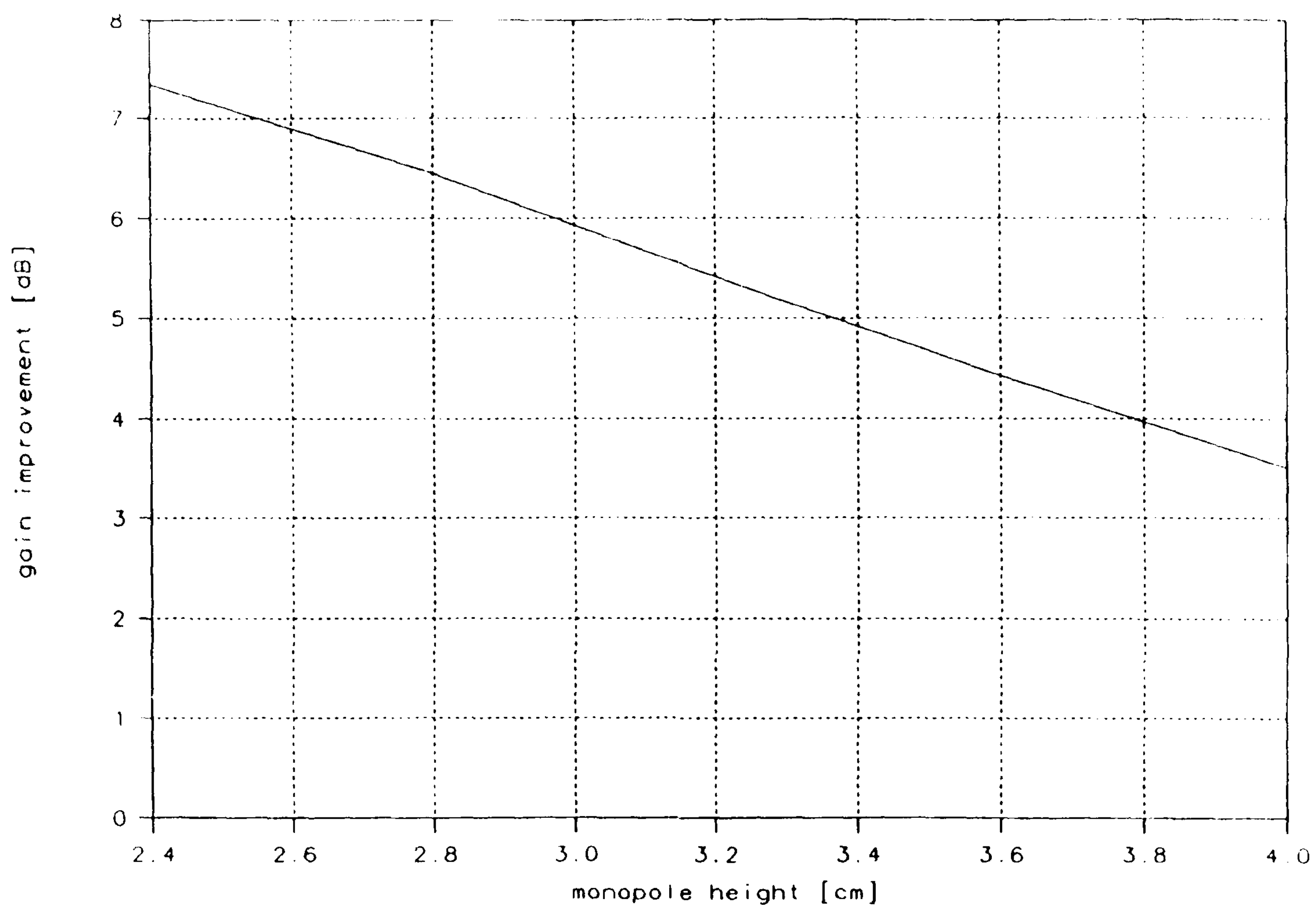


FIGURE 4. PREDICTED ANTENNA GAIN IMPROVEMENT AS A FUNCTION OF MONOPOLE ANTENNA HEIGHT OF AN HTS MATCHING NETWORK COMPARED TO A GOLD MATCHING NETWORK AT LIQUID NITROGEN TEMPERATURE AND FREQUENCY OF 800 MHZ.

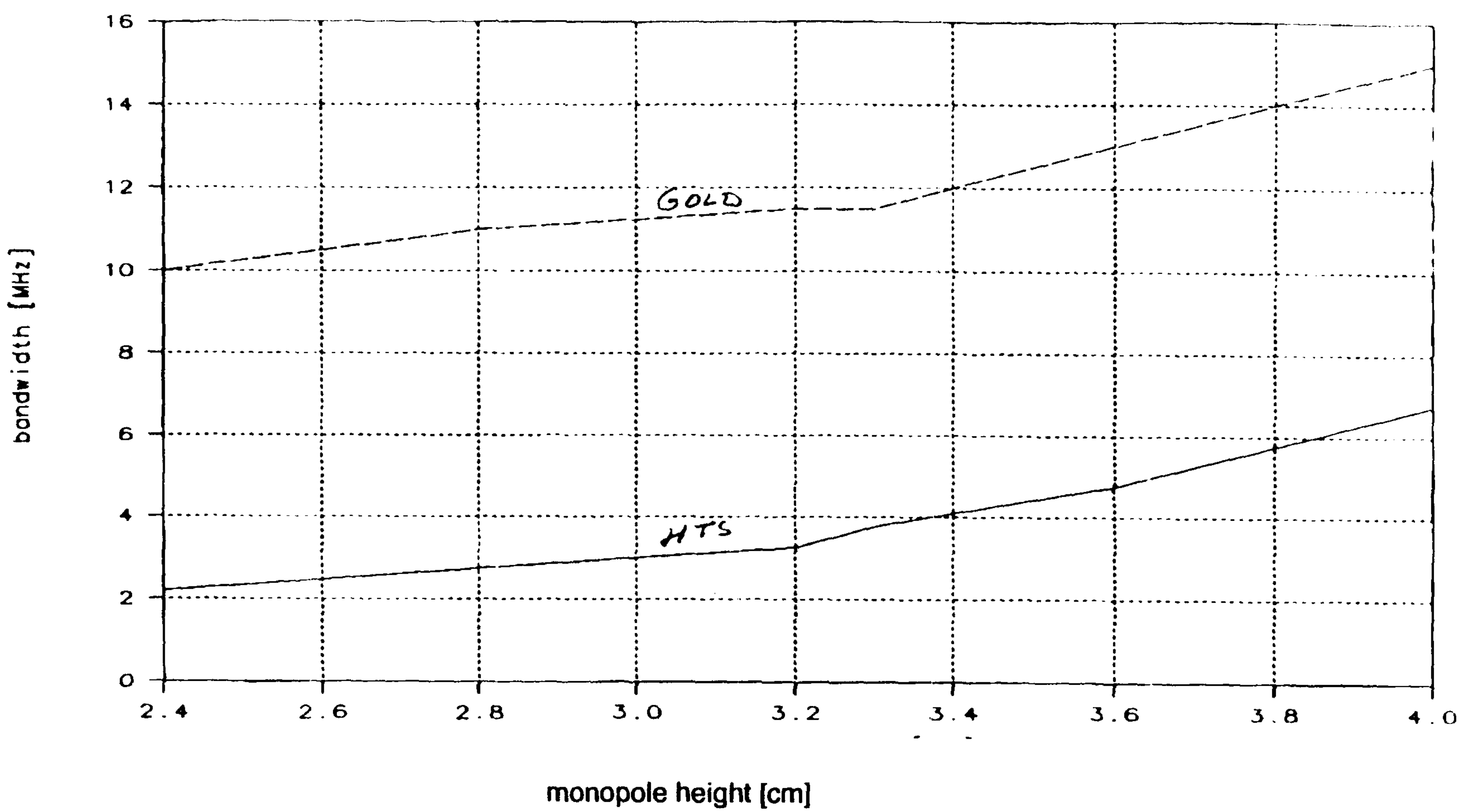


FIGURE 5. PLOT OF THE 3 DB ANTENNA BANDWIDTH AS A FUNCTION OF MONOPOLE ANTENNA HEIGHT OF A GOLD MICROSTRIP SINGLE PARALLEL STUB TUNED MONOPOLE ANTENNA AND OF AN HTS MICROSTRIP SINGLE PARALLEL STUB TUNED MONOPOLE ANTENNA. THE DIAMETER OF THE MONOPOLE ANTENNA IS .91 MM AND THE FREQUENCY IS 800 MHZ.

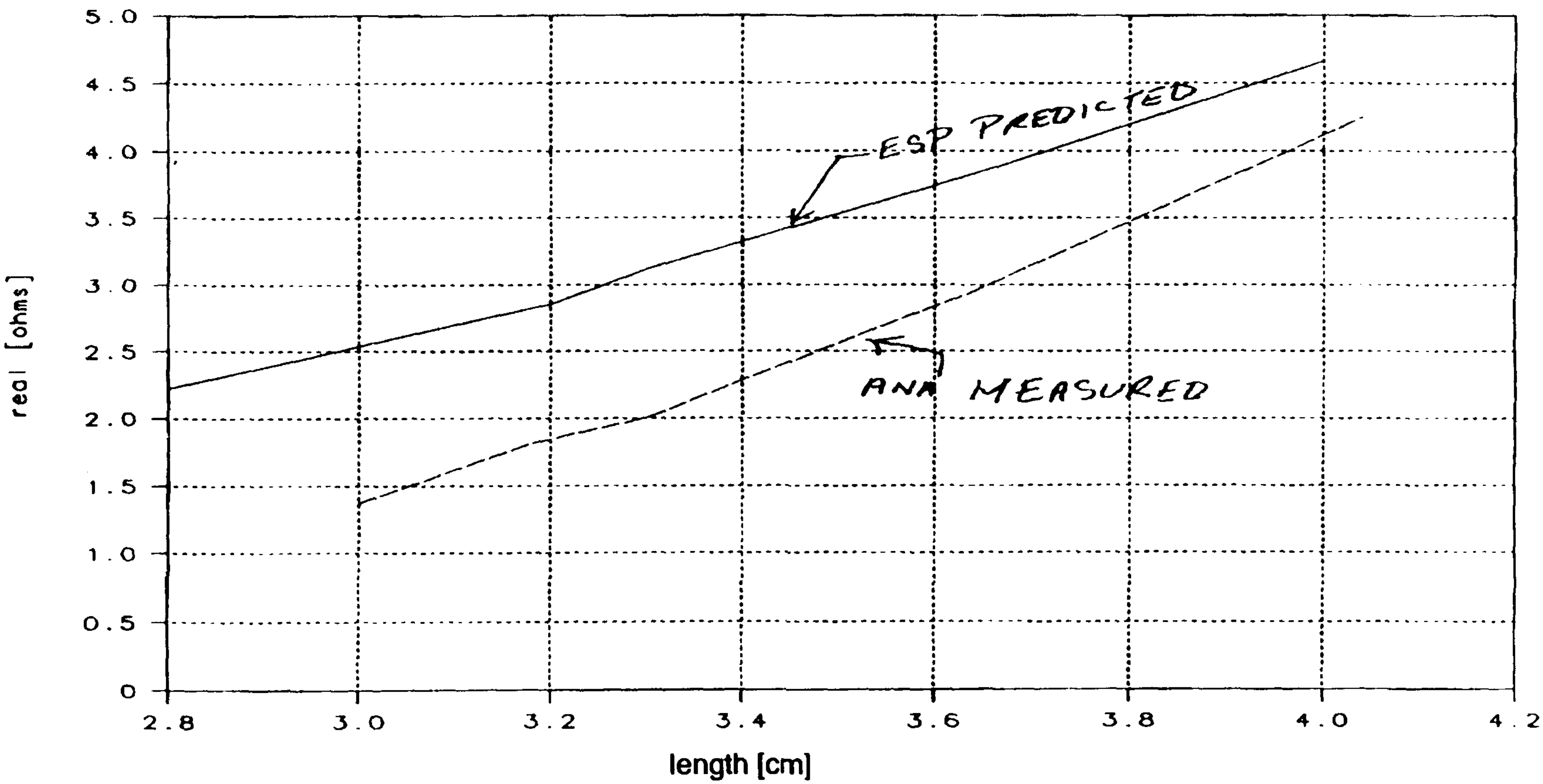


FIGURE 6. PLOT OF THE PREDICTED MONOPOLE IMPEDANCE AND MEASURED MONOPOLE IMPEDANCE AS A FUNCTION OF MONOPOLE LENGTH. THE MONOPOLE DIAMETER IS .91 MM. THE MONOPOLE ANTENNA IS EMBEDDED IN A 22 INCH SQUARE GROUND PLANE. THE FREQUENCY IS 800 MHZ. THE PREDICTED MONOPOLE IMPEDANCE IS FROM ESP, AN OHIO STATE UNIVERSITY CODE.

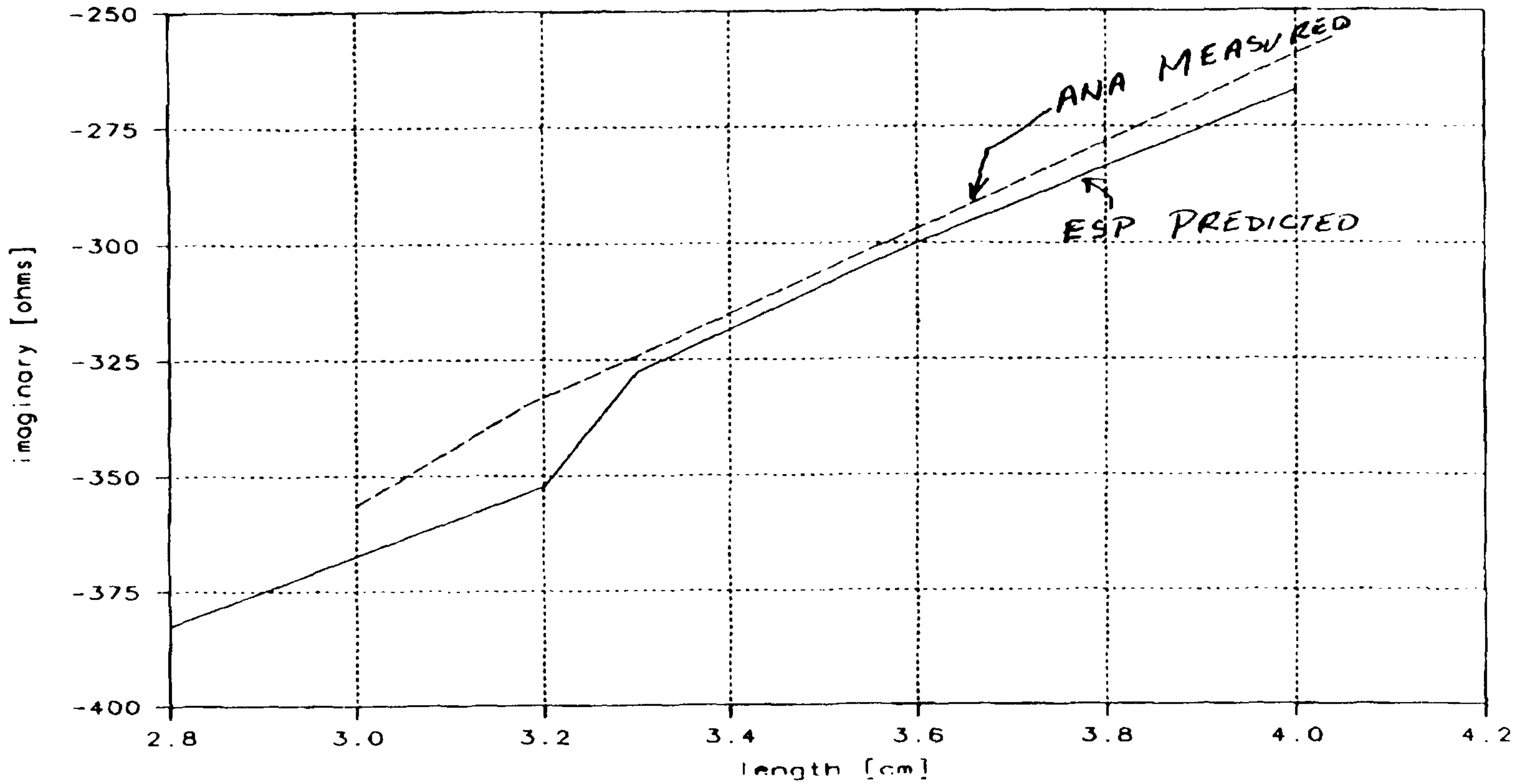


FIGURE 7. PLOT OF THE PREDICTED MONOPOLE IMPEDANCE AND MEASURED MONOPOLE IMPEDANCE AS A FUNCTION OF MONOPOLE LENGTH. THE MONOPOLE DIAMETER IS .91 MM. THE MONOPOLE ANTENNA IS EMBEDDED IN A 22 INCH SQUARE GROUND PLANE. THE FREQUENCY IS 800MHZ. THE PREDICTED MONOPOLE IMPEDANCE IS FROM ESP, AN OHIO STATE UNIVERSITY CODE.

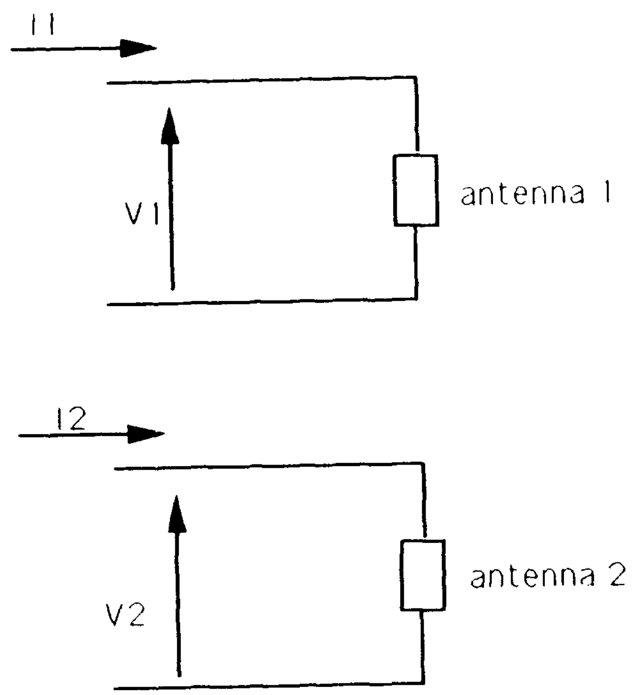


FIGURE 8 SCHEMATIC OF TWO ANTENNAS RADIATING Z11 IS THE SELF IMPEDANCE OF THE FIRST ANTENNA Z12 IS THE MUTUAL IMPEDANCE BETWEEN THE F RST AND SECOND ANTENNAS

for the two element antenna array can be written as:

$$Z_{1A} = V_1/I_1 = Z_{11} + Z_{12}\,(I_2/I_1)$$

and

$$Z_{2A} = V_2/I_2 = Z_{12}\,(I_1/I_2) + Z_{22}.$$

The ESP input is V_1 and V_2 and the ESP output is $\underline{I}$ and [Y] where $\underline{I}$ is the current of the radiating antenna elements and of the ground plane surface patches and [Y] is the admittance matrix of the radiating elements and of the ground plane surface patches. The radiation pattern is determined by the current elements hence, the voltage elements must be specified such that the current elements produce the desired radiation pattern.

A general algorithm for choosing the voltage elements such that the current elements give the desired radiation pattern is given below. In general one can write

$$\underline{I} = [Y]\,\underline{V}.$$

In order to determine the desired voltage excitations solve:

$$\underline{\mathbf{I}}_1 = [Y]\,\underline{\mathbf{V}}_1 \quad , \quad \text{where } \underline{\mathbf{V}}_1 = [1000\ldots\ \ ]^T,$$
$$\underline{\mathbf{I}}_2 = [Y]\,\underline{\mathbf{V}}_2 \quad , \quad \text{where } \underline{\mathbf{V}}_2 = [0100\ldots\ \ ]^T, \text{ and}$$
$$\underline{\mathbf{I}}_n = [Y]\,\underline{\mathbf{V}}_n \quad , \quad \text{where } \underline{\mathbf{V}}_n = [000\ldots\ 01]^T.$$

The desired antenna distribution, $\underline{\mathbf{I}}_{antenna}$, can be found from superposition:

$$a_1\underline{\mathbf{I}}_1 + a_2\underline{\mathbf{I}}_2 + \ldots\ldots + a_n\underline{\mathbf{I}}_n = \underline{\mathbf{I}}_{antenna}$$

or

$$[\underline{\mathbf{I}}_1, \quad \underline{\mathbf{I}}_2, \ldots \underline{\mathbf{I}}_n] \quad \underline{a} = \underline{\mathbf{I}}_{antenna}$$

Once $\underline{a}$ has been determined, the appropriate voltages are:

$$\underline{\mathbf{V}}_1 = [a_1, 0, 0, 0 \ldots, 0]^T,$$
$$\underline{\mathbf{V}}_2 = [0, a_2, 0, 0, 0 \ldots 0]^T,$$
$$\underline{\mathbf{V}}_n = [0, 0, \ldots, 0, a_n]^T.$$

This approach was not necessary for the design of the two element antenna array. For the two element array, specifying the voltages resulted in the necessary radiating currents.

In order to design a four element array however, the currents had to be specified and the voltages then solved for.

For both the two and four element array, the goal was to design an endfire array which had greater gain than an ordinary endfire array and had impedances which could be reasonably matched. Impedances which could be reasonably well matched with a single stub matching network were in the range of 2 to 3 ohms for the real part and 200 to 300 ohms for the imaginary part.

Due to financial cutbacks a two element array rather than a four element array was built and tested. Once the input impedance had been determined from ESP, the individual single stub matching networks were built. The physical dimensions of the single stub matching networks were determined from Touchstone.

In order for the two element array to perform adequately there were some mechanical issues which had to be addressed. The design objective for the two element array was to create a fixture which would adequately heat sink the matching network to the liquid nitrogen. In addition, the rate of liquid nitrogen evaporation had to be reduced making it necessary to insulate the dewar opening and the heat path through to the ground plane.

Experiments with the single element fixture had shown that the radiator was a source of heat input to the matching network. Providing an alternate path for the heat before it reached the housing of the matching network solved the problem. For the two element array this alternate path was provided by means of an aluminum block in the shape of a tee. The connector flanges of the radiating elements were mounted on the arms of the tee. The matching networks were mounted on a copper bar which was also mounted on a tee (see figure 9). The tee block held the elements at the correct spacing as well as providing a central structure for conveniently mounting the other components. At the end of the copper bar there was a block of aluminum finstock for more efficient transfer of heat to the liquid nitrogen.

Experience with the single element monopole antenna had shown that the large ground plane acted as a heat collector which forced us to move from a solid aluminum plate to a laminate plate which consisted of a thin aluminum covering, a foam core, and

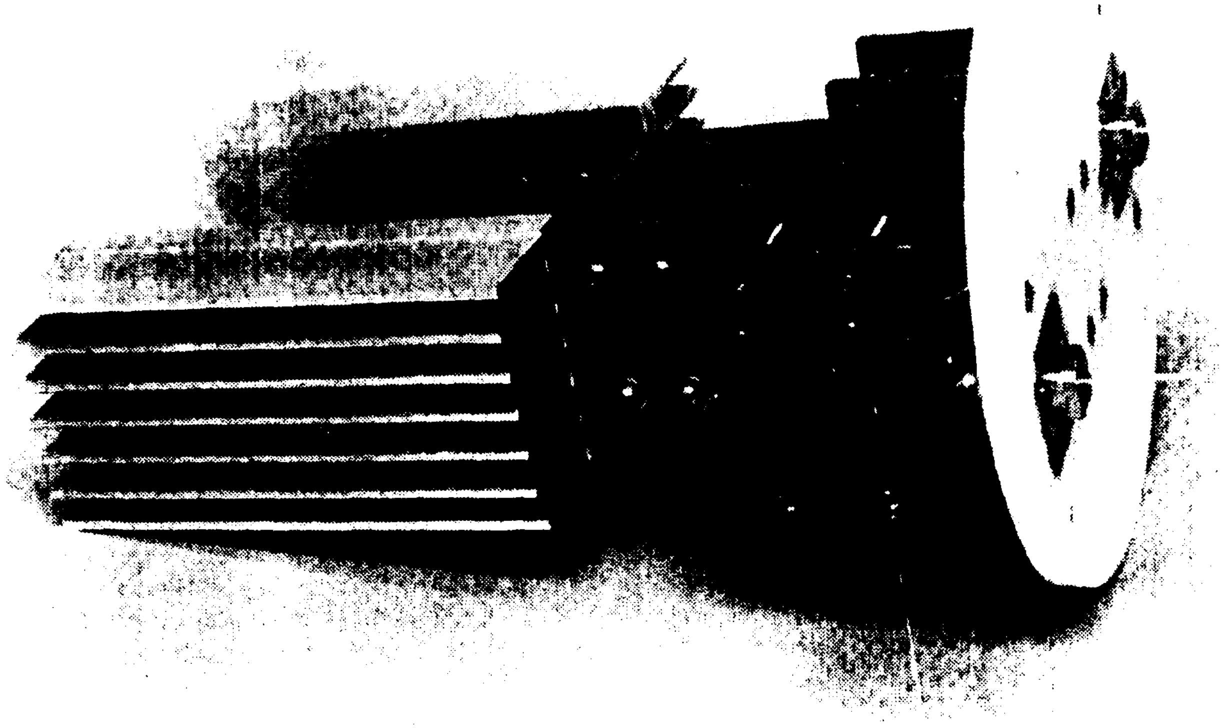


FIGURE 9. TWO ELEMENT ARRAY ASSEMBLY SHOWING MONOPOLES, MATCHING NETWORKS, COPPER BARS, FIN STOCK, AND TEE BLOCK.

an epoxy backing. The reduced rigidity and the higher thermal gradients produced by the laminate plate were sufficient to create unacceptable warping of the ground plane. To reduce warping to an acceptable level, rigid foam blocks were attached to the underside of the ground plane around its perimeter (see figures 10 and 11). Additional insulation of the ground plane was provided by the delrin disk which covered the majority of the open end of the dewar (see figure 12). The foam ring which can be seen in figure 11 (not shown in position of use) covered the remainder of the dewar's open end and allowed the dewar to "breathe" to prevent pressure build up.

When in use the fixture shown in figure 10 was turned upright with the antenna elements pointing straight up. The dewar was centered under the ground plane and covered the matching networks and the array fixture all the way up to just below the delrin disk. Connection to the matching networks was accomplished by cryogenic RF cables which came up and out over the rim of the dewar to interface with the couplers, see figure 11.

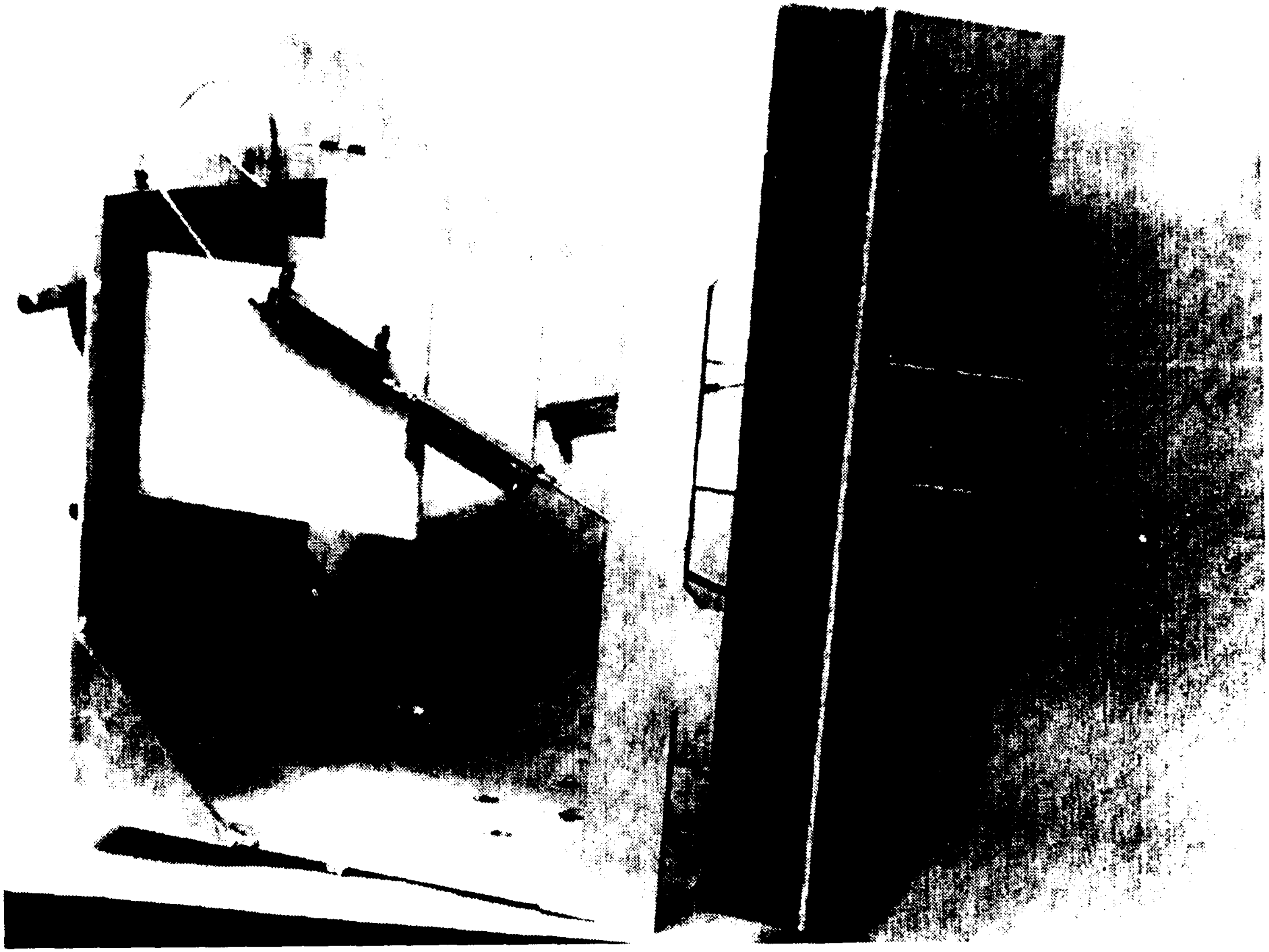


FIGURE 10. TWO ELEMENT ARRAY GROUND PLANE AND RANGE FIXTURE.

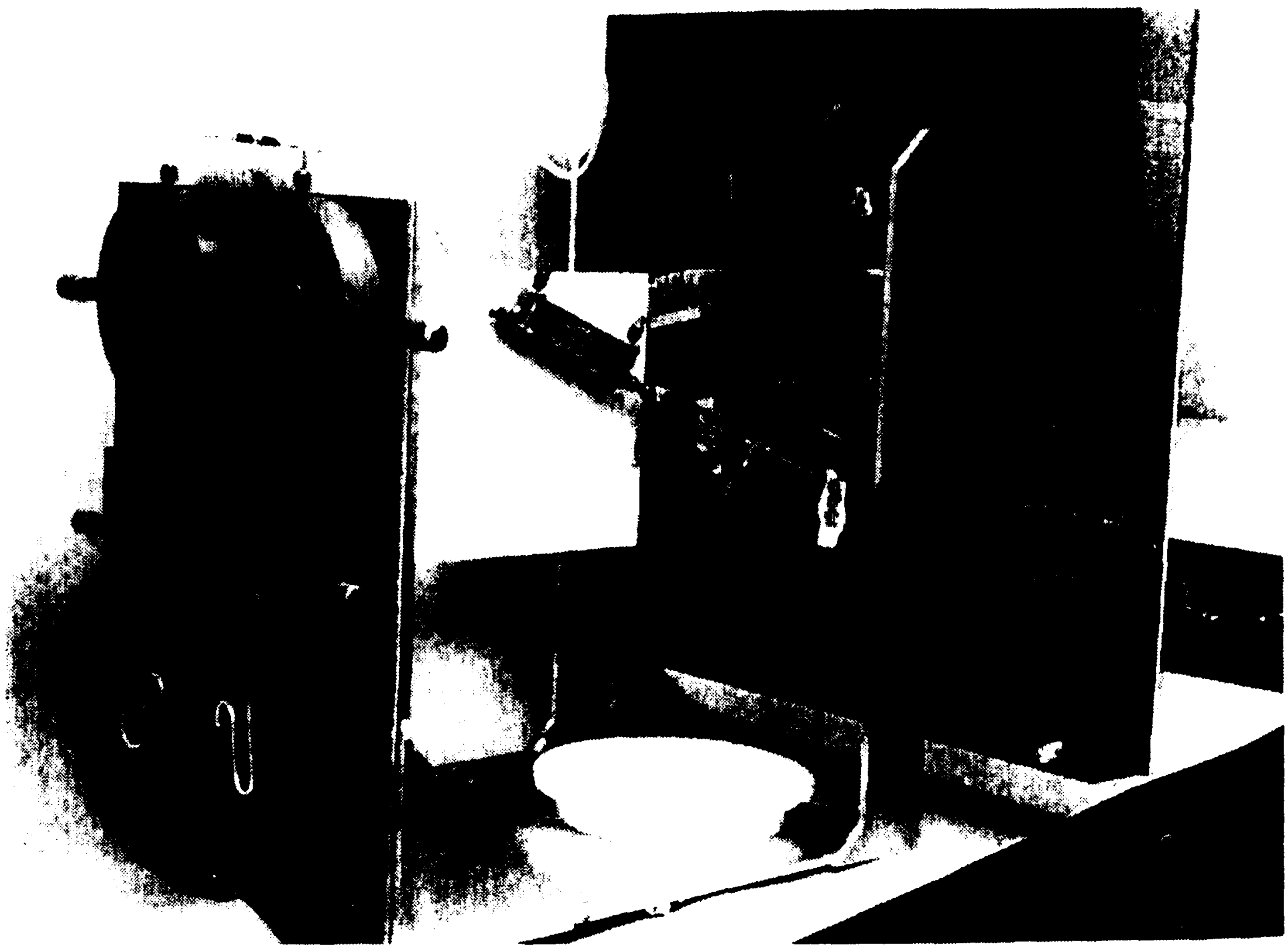


FIGURE 11. RANGE FIXTURE FOR THE TWO ELEMENT ARRAY.

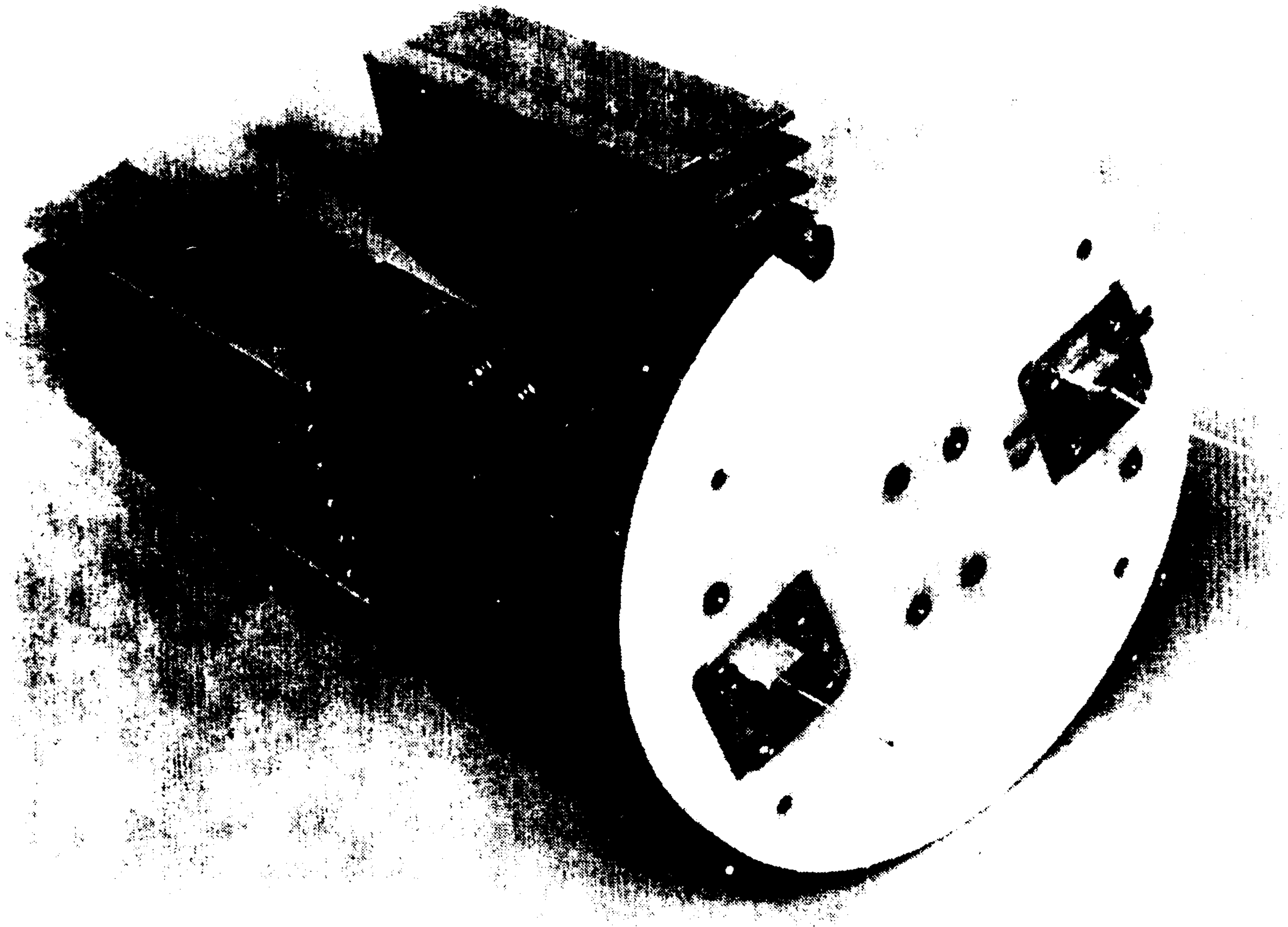


FIGURE 12. DELRIN DISK ADDS INSULATION
AT DEWAR OPENING

FILM GROWTH -Final Report

The HTS films used in this program were exclusively $YBa_2Cu_3O_7$ (YBCO), deposited on (100) $LaAlO_3$ substrates by off-axis sputtering. The deposition techniques were developed and published as part of other programs.[2] Briefly, a single, stoichiometric YBCO target was sputtered in a reactive gas mixture of 100 mtorr O_2, 100 mtorr Ar, and 20 mtorr H_2O. Both dc and rf magnetron sputtering were used without apparent differences in film properties. The substrate was positioned with its normal perpendicular to a line normal to the target. The substrate was heated to approximately 720° C during deposition. After deposition, the O_2 pressure was raised to 20 torr, the sample was cooled to 400° for a 20 ... soak, and then cooled to room temperature.

The method used to heat the substrate during deposition evolved during the course of this project. Following a procedure that is standard for HTS film growth, the first substrates were bonded to a nickel block with silver paint. The block was heated radiatively from behind. A thermocouple was embedded in the block for temperature measurement. This technique worked well for small samples, $\leq$ 1cm^2. Larger samples as required by this project, about 2.5 cm x 2.5 cm, showed some inhomogeneity due to bubbles that were trapped in the silver paint during its curing cycle. The inhomogeneity was visible in such films, although measurements of T_c, J_c, and rf surface resistance, R_s, showed good uniformity.[3] A more serious problem was the high probability of breakage and resultant low yield of large-area substrates when they were removed from the nickel block.

The last four matching networks fabricated in this project used YBCO films deposited on two-inch diameter $LaAlO_3$ wafers which were heated directly by radiation while resting on a transparent $LaAlO_3$ holder. Westinghouse was first in developing a heater of this type for large area substrates.[4] There are several advantages to direct radiative heating. The yield for films made by this process is approximately 95%. The films had a completely uniform appearance. Perhaps most importantly, both sides of the substrate could be coated with YBCO. Two sided deposition permitted microstrip transmission line structures to be fabricated on a single wafer instead of two stacked wafers. The single wafer minimized mechanical problems, eliminated the possibility of air gaps, and simplified contact to the ground plane.

Some uncertainty still remains on the value of the rf surface resistance, R_s, of YBCO deposited on 2-inch diameter $LaAlO_3$ wafers heated solely by radiation. Measurements of R_s performed on small chips cut from these wafers indicate that the typical R_s was 0.7 milliohms at 77K and 10 GHz on either side of the wafer. Since R_s is proportional to the square of frequency for superconductors, 0.7 milliohms at 10 GHz extrapolates to a factor of 750 improvement over Cu at 800 MHz. Although R_s was uniform across a wafer to within $\pm$ 30%, the average R_s from one wafer to another ranged from 250 to 1500 times lower than copper at 800 MHz and 77K.

FABRICATION - Final Report

The matching network configuration chosen for this project was a single stub tuner. Early on in the program the need for compactness was recognized, since at the time wafers even as large as the 1 in.-by-1 in. needed had never been grown before. A center frequency of 800 MHz was chosen instead of the 500 MHz originally proposed in order to make the device smaller. It was also decided not to introduce any bends in the transmission line and stub in order to keep the design as simple as possible. The matching network was to be packaged independently of the antenna, which meant that it was inserted between 50 ohm connectors. At the antenna end, the monopole itself was terminated in a 50 ohm coaxial line and connector. This is illustrated in figure 13, which shows, schematically, the entire monopole antenna assembly, including cooling. The electrical lengths of the connectors and the microstrip-to-coaxial transition had to be considered as part of the matching network design.

A total of seven matching networks were fabricated. Their characteristics are summarized in Table 1. Two of them were made in gold and were designed for operation at room temperature and 77K, respectively. This was felt to be an important part of the project because it provided a reference point against which to compare the performance of the superconducting devices. Three single matching networks were made in YBC0. Two more were designed as a two-element superdirective array.

The single YBCO matching networks, which could be compared directly with the gold ones, reflected the improvements in fabrication technology throughout the program. The first was made using single-sided YBCO and therefore two substrates were needed, one for the device proper and the other for the ground plane. The device was fabricated using a wet etching technique which yielded very poor pattern definition and quality. The films were grown using the technique requiring silver paint to attach the substrate to the heater block (see previous section), and had a very low yield. These were the first substrates grown by us on what then was a large area substrate (1 inch square).

The second matching network used a YBCO film grown on both sides of a 2-inch-diameter $LaA1O_3$ substrate. Ion milling was used in the patterning, which gave very good definition and no defects. The substrate was cut first, however, and then processed. This

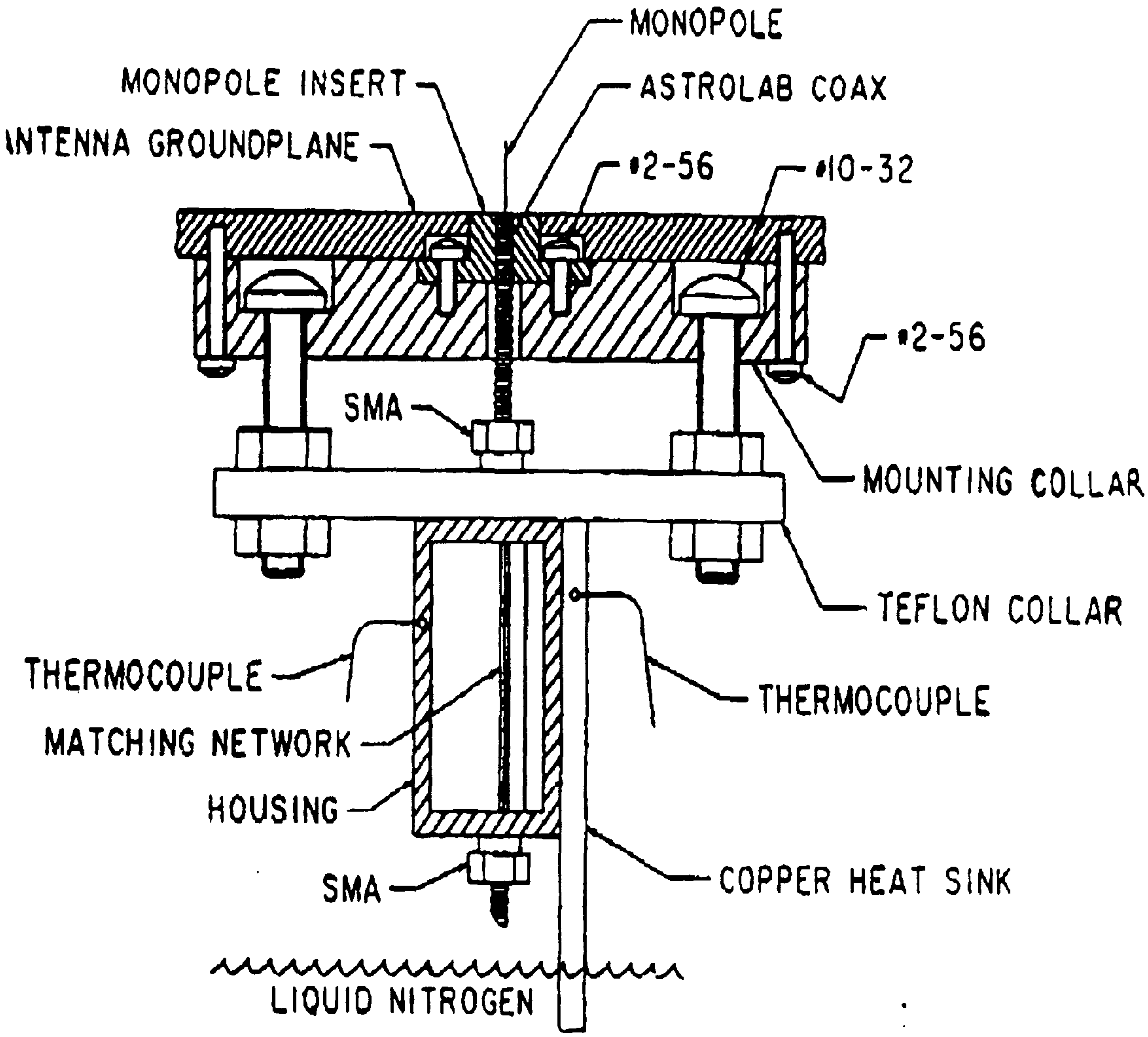


FIGURE 13. MONOPOLE ANTENNA ASSEMBLY.

is not optimal, however, because the photoresist layer spun on a non-circular substrate tends to have a non-uniform thickness, resulting in poor pattern definition near the edges of the substrate. This problem was remedied in all subsequent matching networks fabricated, which were processed from a full wafer and were diced as the last step before mounting in the package. In all cases where a 2-inch-diameter, double-sided substrate was used, the area surrounding a central 1-inch-square occupied by the device was used for testing the quality of the film. With full-wafer processing, this meant that the pieces used for testing had undergone all the fabrication steps of the device itself and therefore provided a good measure of the film quality of the fabricated device.

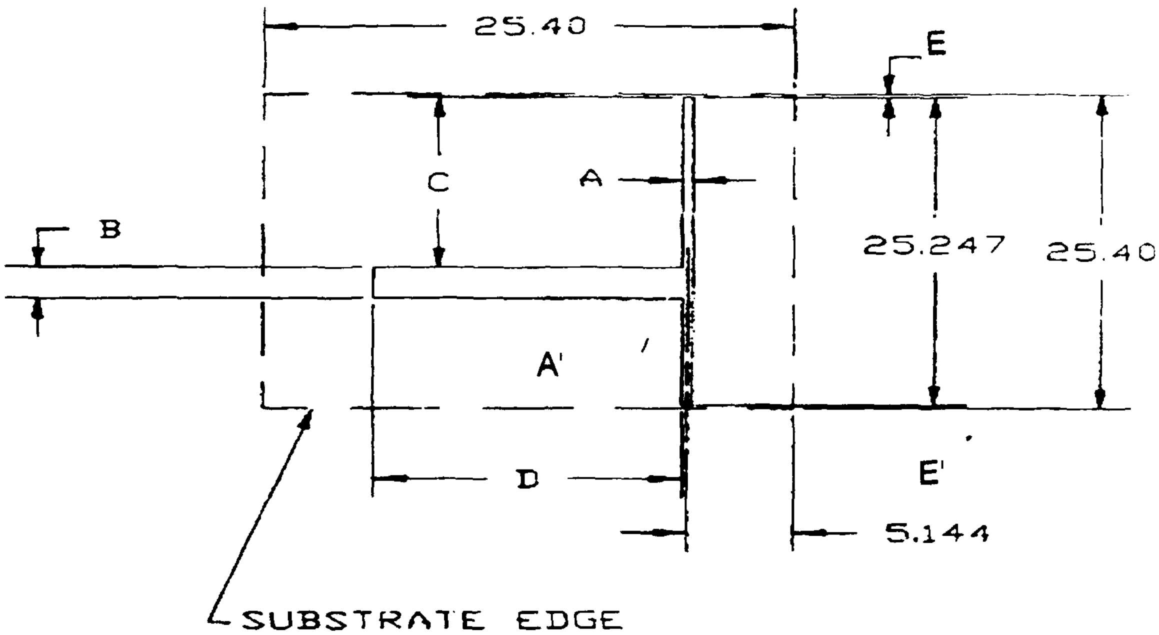
WAFER-PROCESSING - Final Report

Processing of the YBCO film followed standard photolithographic techniques. Opaque chrome masks were made for all the matching networks designed. The pattern was defined in the YBCO film for the first device made (see Table 1) using a room-temperature phosphoric acid solution. This technique had been used successfully for filters and resonators fabricated on smaller area substrates. Because the etch rate was very high, good pattern definition was hard to achieve using wet etching on a relatively large area such as that needed here. Therefore, subsequent matching networks were defined using ion milling. Although some initial problems having to do with the proper adjustment of the etch rate had to be overcome, once the technique for ion milling YBCO was established the results were very satisfactory, yielding excellent pattern definition with no defects or appreciable overetching.

Electrical contact to the YBCO matching network was made through 2000-A-thick by 2-mm-long gold contact pads overlaying the 50 ohm input and output lines of the device. The gold was deposited by evaporation. The pads were defined on the input and output lines by lift-off, as a second level photolithographic process. After this the substrate was cleaned and annealed in dry oxygen at 600° to insure a low-resistance contact between the gold and the YBCO microstrip line.

Figure 14 presents a summary of the matching network pattern dimensions fabricated in gold and YBCO. As can be seen in Table 1, the first three designs were for 0.017-inch thick $LaAlO_3$ and the next four for 0.020-inch $LaAlO_3$. The reason for the change is that the substrate supplier (AT&T) changed its standard substrate thickness from 0.017 in. to 0.020 in. A decision was made then to adjust to the new standard in order to insure ready availability of substrates.

Figure 15 is a diagram of the full-wafer mask used for the last three matching networks fabricated (see Table 1), showing the 1/4" x 1/2" sample testing pieces defined around the matching networks. The entire pattern was defined on a 2-inch diameter wafer coated on both sides with YBCO. After patterning by ion milling the gold contact pads were defined as described above. After annealing the wafer was diced along the defined cutting lines, shown in the figure. Thus, the cutting was carried out with a dimensional



NOTE: ALL DIMENSIONS ARE IN MILLIMETERS.

FIGURE 14. DIMENSIONS (IN MM) FOR ALL THE MATCHING NETWORKS FABRICATED.

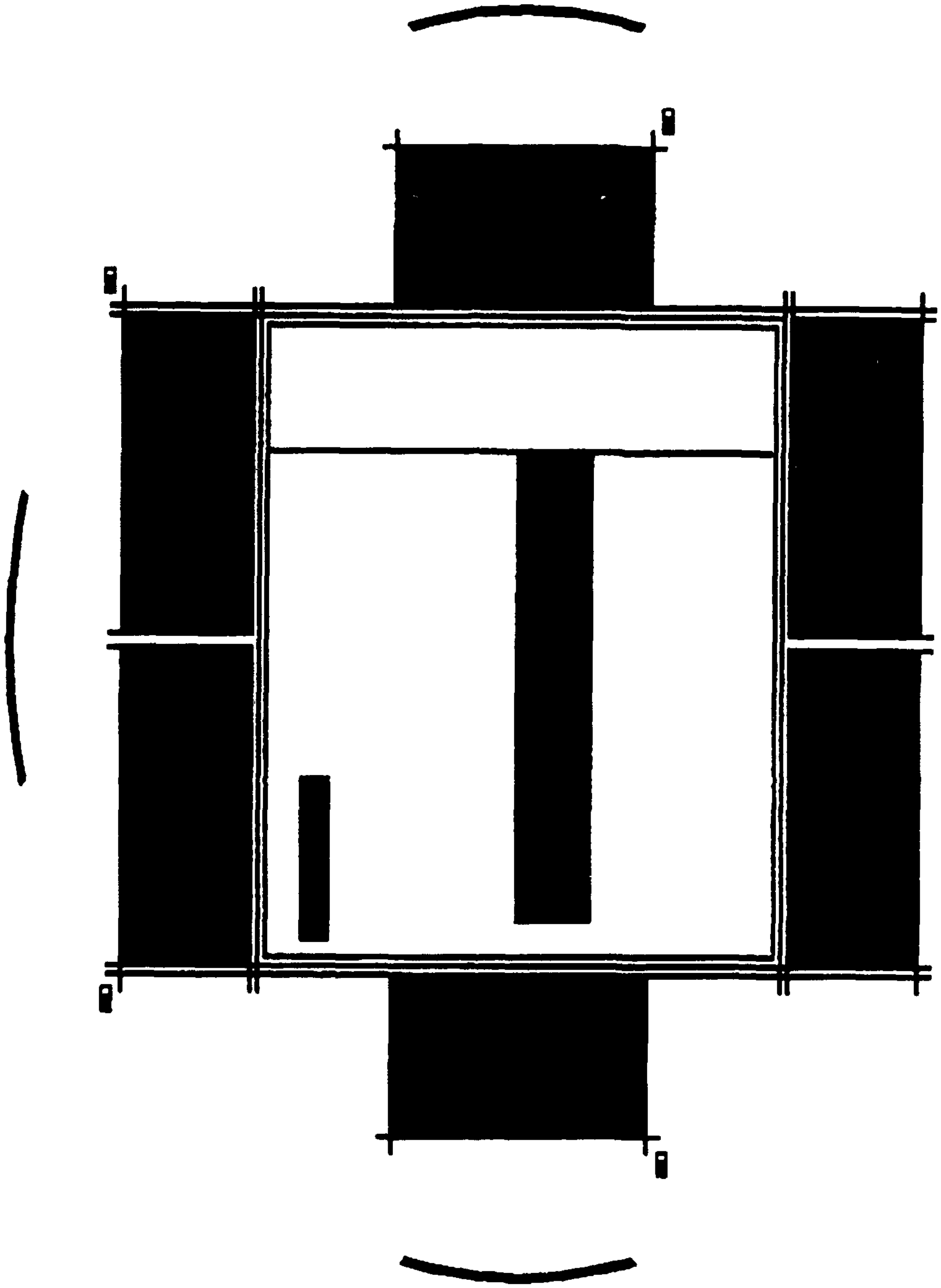


FIGURE 15. FULL WAFER MASK PATTERN USED FOR THE LAST FIVE MATCHING NETWORKS FABRICATED INCLUDING TEST PIECES

TABLE 1

MATCHING NETWORK CHARACTERISTICS

DEVICE		DIMENSION (MM)						
ID	DESCRIPTION	A	A'	B	C	D	E	E'
MN-90113-3.3	AU (300K)	.129	.129	2.553	14.039	14.740	.051	.102
MN-90113-2.4	AU (77K)	.129	.129	2.570	13.490	16.855	.051	.102
MN-90113-1.4	YBCO (77K)	.141	.141	3.327	12.786	18.694	.051	.102
MN-910228-1.5	YBCO (77K)	.144	.166	3.818	12.409	18.942	.051	.102
MN-910228-1.6	YBCO (77K)	.144	.166	3.818	12.409	18.942	.102	.102
SD-1.0	YBCO (77K)	.145	.167	3.665	12.103	19.096	.102	.102
SD-2.0	YBCO (77K)	.146	.167	3.662	12.096	19.010	.102	.102

tolerance of only a few microns, since one edge of the 0.006-inch-thick blade could be positioned directly on the 0.005-inch-wide cutting lines. A high precision, high speed circular wafer saw was used for this. The test pieces produced this way underwent all the fabrication steps as the device itself and therefore provided a good measure of its quality.

CHARACTERIZATION

The YBCO films for the last three matching networks were fabricated using the whole-wafer approach. They were evaluated through the test pieces defined on the YBCO wafer around the device. This had the advantage that the test pieces underwent all the fabrication steps as the device itself. Matching network MN-910228-1.S, made immediately before the whole wafer approach was introduced (see table 1), had accompanying test pieces which were evaluated also. However, in this case the test pieces were cut before the matching network fabrication began and therefore were not subjected to all the processing steps. Nevertheless, the tests performed are believed to have provided valuable information.[3]

Three types of measurements were carried out at the same time using the experimental arrangement shown schematically in figure 16. Four contact pads were placed on the YBCO film surface using silver paste, in order to make Van der Paw resistivity measurements, with the polaritics of current and voltage indicated in the diagram. At the same time, the inductance variation with temperature of a coil placed on the film surface was measured at 100 KHz. Thus, two different measurements of transition temperature T_c were obtained: a DC one, from the Van der Paw resistivity, and an AC measurement, which samples a larger area of the film. The DC resistivity at temperatures above T_c measured is another measure of the quality of the film, 250 micro ohms-cm being a typical result at 300 K. In a good quality film, this room temperature resistivity scales linearly with temperature down to T_c, and extrapolates to zero below T_c. Figures 17a and b show examples of these measurements for the YBCO films on both sides of a substrate. More information can be found in reference 3.

The microwave surface resistance was measured using a slight modification of the technique developed by Taber.[5] It consists of forming a low Q, parallel plate resonator with a pair of the test pieces. For the resonator to have a significant loss contribution from the currents in the films, the spacing between plates is chosen to be very small, on the order of 12 to 25 micrometers. Teflon of Kapton was used for this purpose. Since the test samples had a large area (0.5" x 0.25") relative to their spacing from each other, the resulting resonator had a low unloaded Q, on the order of 700 to 1000 GHz at 8 GHz (assuming a frequency squared surface resistance dependence). A typical example of this type of measurement on a film used for one of the matching networks made is shown in figure 18.

Table 2 presents a summary of the film evaluation for the last four matching networks fabricated.

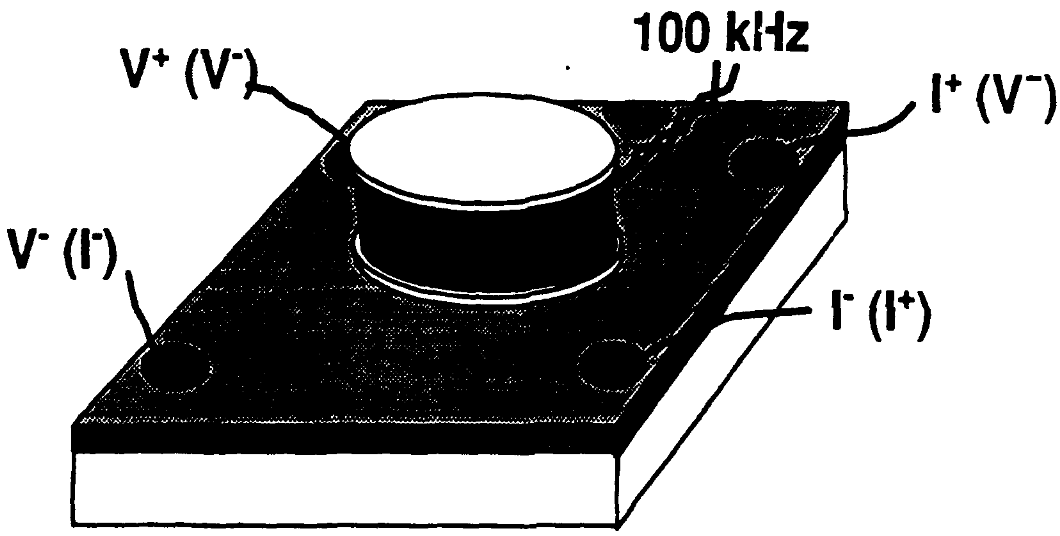


FIGURE 16. EXPERIMENTAL RESISTANCE USED FOR THE RESISTIVITY (VANDER PAW) AND VARIABLE INDUCTANCE VS. TEMPERATURE MEASUREMENTS ON YBCO FILMS.

MIKE2.datM-DRW

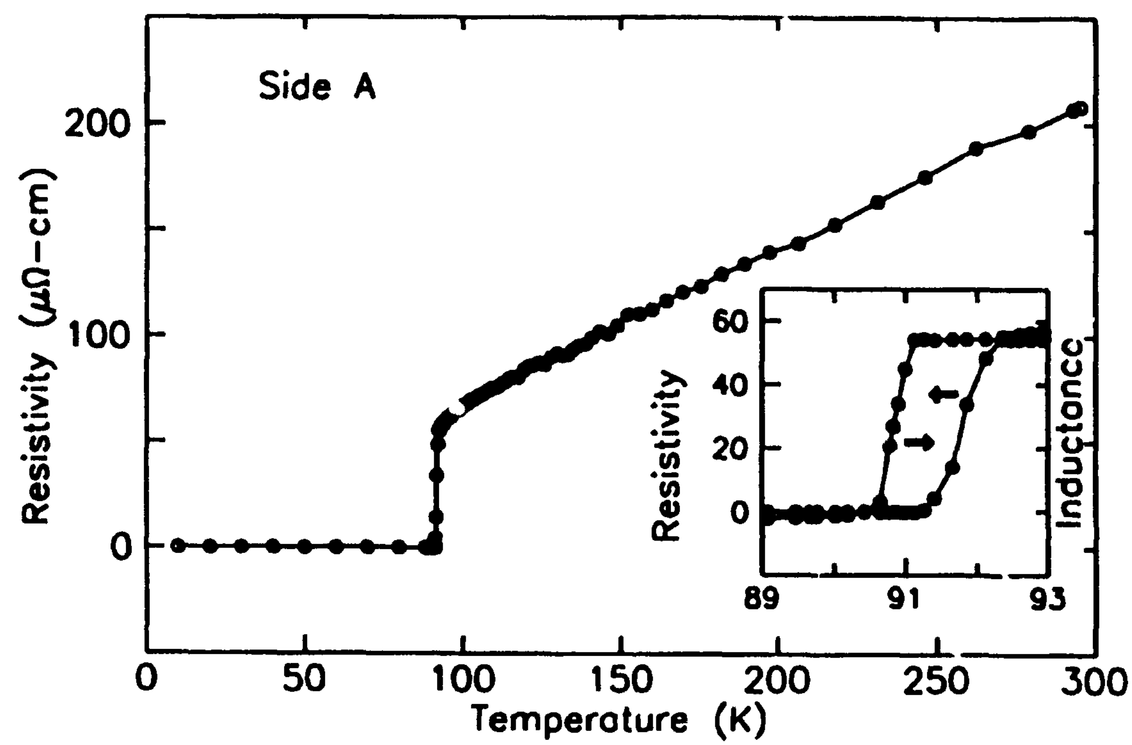


FIGURE 17a. RESISTIVITY VS. TEMPERATURE FOR DOUBLE-SIDED YBCO FILM DEPOSITED ON SIDE A OF A 2-INCH DIAMETER LaAl03 WAFER. THE INSET FIGURE COMPARES THE RESISTIVE AND INDUCTIVE TRANSITIONS.

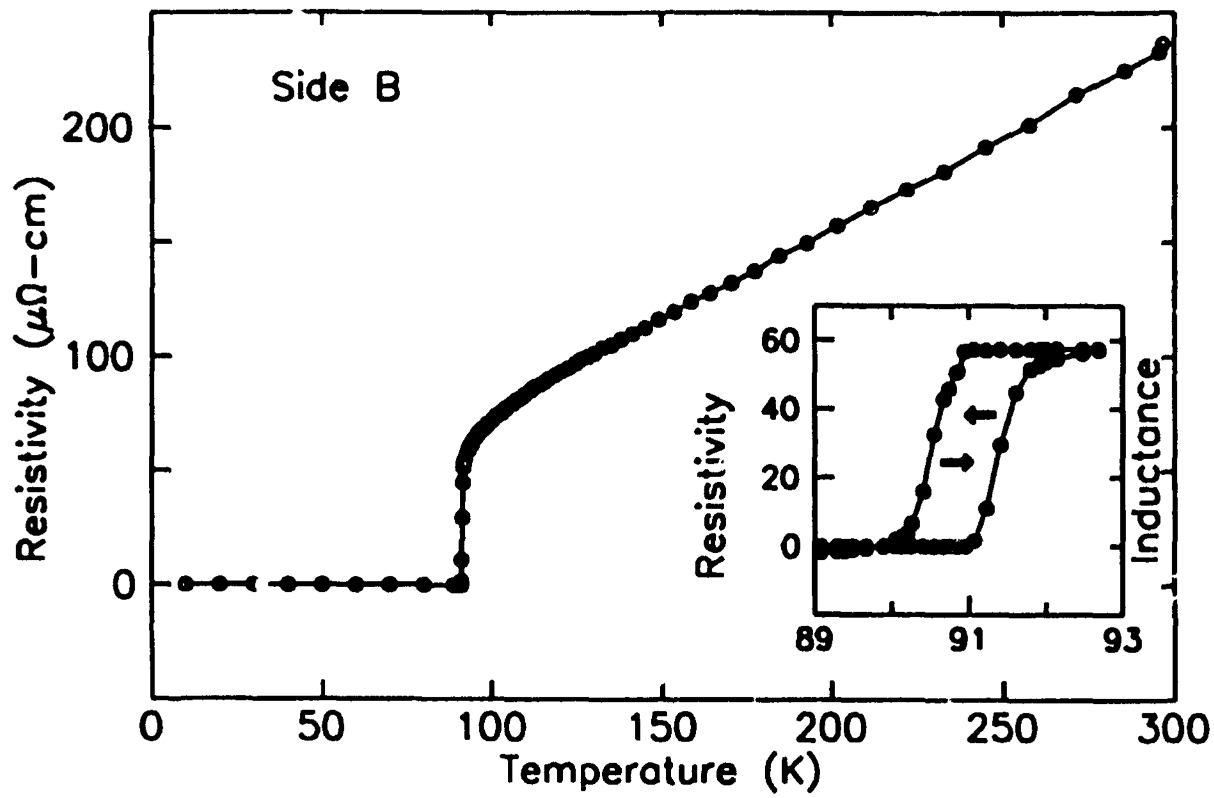


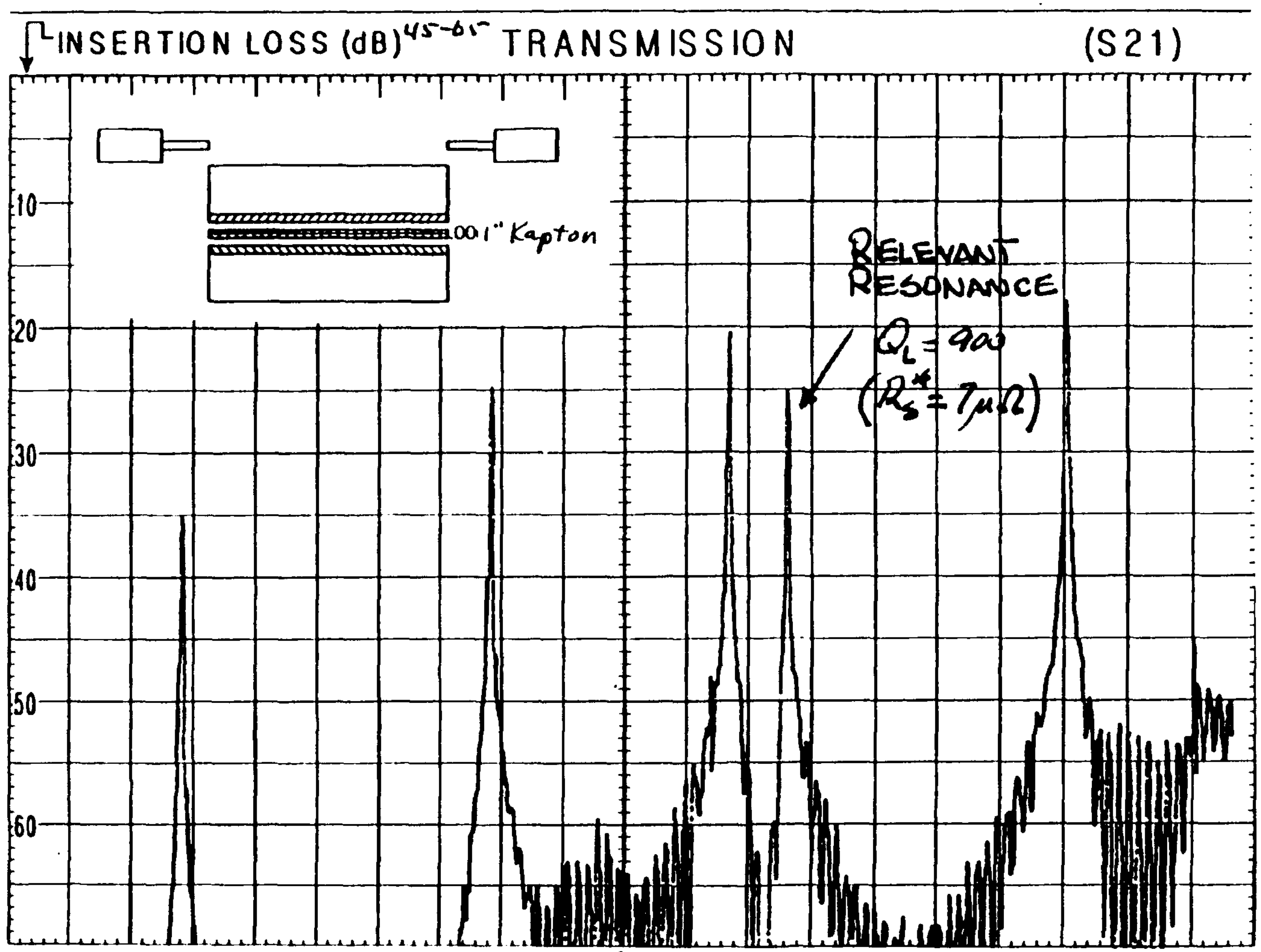
FIGURE 17b. RESISTIVITY VS. TEMPERATURE FOR DOUBLE-SIDED YBCO FILM DEPOSITED ON SIDE B OF A 2-INCH DIAMETER $LaAlO_3$ WAFER. THE INSET FIGURE COMPARES THE RESISTIVE AND INDUCTIVE TRANSITIONS.

MIKE SIDE B datM PM

TABLE 2

COMPARISON OF HTS AND GOLD MATCHING NETWORKS

	HTS MATCHING NETWORK		GOLD MATCHING NETWORK
monopole length	3.18		3.20
coax feed design and material		identical	
coax feed length		identical (.7")	
coax to microstrip transition design		identical	
microstrip dielectric material	20 mils thick $LaAlO_3$		17 mils thick $LaAlO_3$
matching network design objective	maximize $/S_{21}/^2$ minimize $/S_{11}/^2$		maximize $/S_{21}/^2$ minimize $/S_{11}/^2$
microstrip line length from coax feed to stub	.487"		.531"
microstrip line width	.0057"		.0051"
stub length	.7448"		.6636"
stub width	.1491"		.1012"
antenna ground plane		identical (22" x 22")	
antenna radome		identical	



CENTER FREQUENCY: 7.0 GHz

FIGURE 18. EXAMPLE OF THE PARALLEL-PLATE RESONATOR MEASUREMENT USED TO OBTAIN THE MICROWAVE SURFACE RESISTANCE OF YBCO FILMS

MIKE 1 DRW datM

PACKAGING - Final Report

Packaging design and assembly are critical issues for microwave cryogenic devices. It is not only important that the package be electromagnetically sound, designed to minimize parasitic reactances and electromagnetic coupling between input and output, but that it be mechanically stable so it can withstand thermal cycling without degradation of its electrical characteristics.

The packaging techniques used for the matching networks fabricated in this program were developed under contracts from the Navy (NRL) and the Air Force (WRDC). The specific dimensions of the package used here are given in figure 19. Figure 20 is an isometric view of how the different components of the package fit together. Figure 21 shows a detail of how the connector and the substrates are arranged. The coaxial-to-microstrip transition is accomplished using a Wiltron K-connector, which is based on a glass bead soldered onto the package wall. In these drawings two substrates are shown, illustrating the more complicated case of having a ground plane on a separate substrate, whenever single-sided YBCO was used. In the case of double-sided YBCO, the block supporting the substrates was made thicker and the ground plane was entirely coated with gold. Figure 22 is a photograph of the completed device. For the last three matching networks fabricated holes were drilled on the top lid in order to allow the liquid nitrogen to flow through the device. This was done to insure temperature uniformity throughout the device surface area.

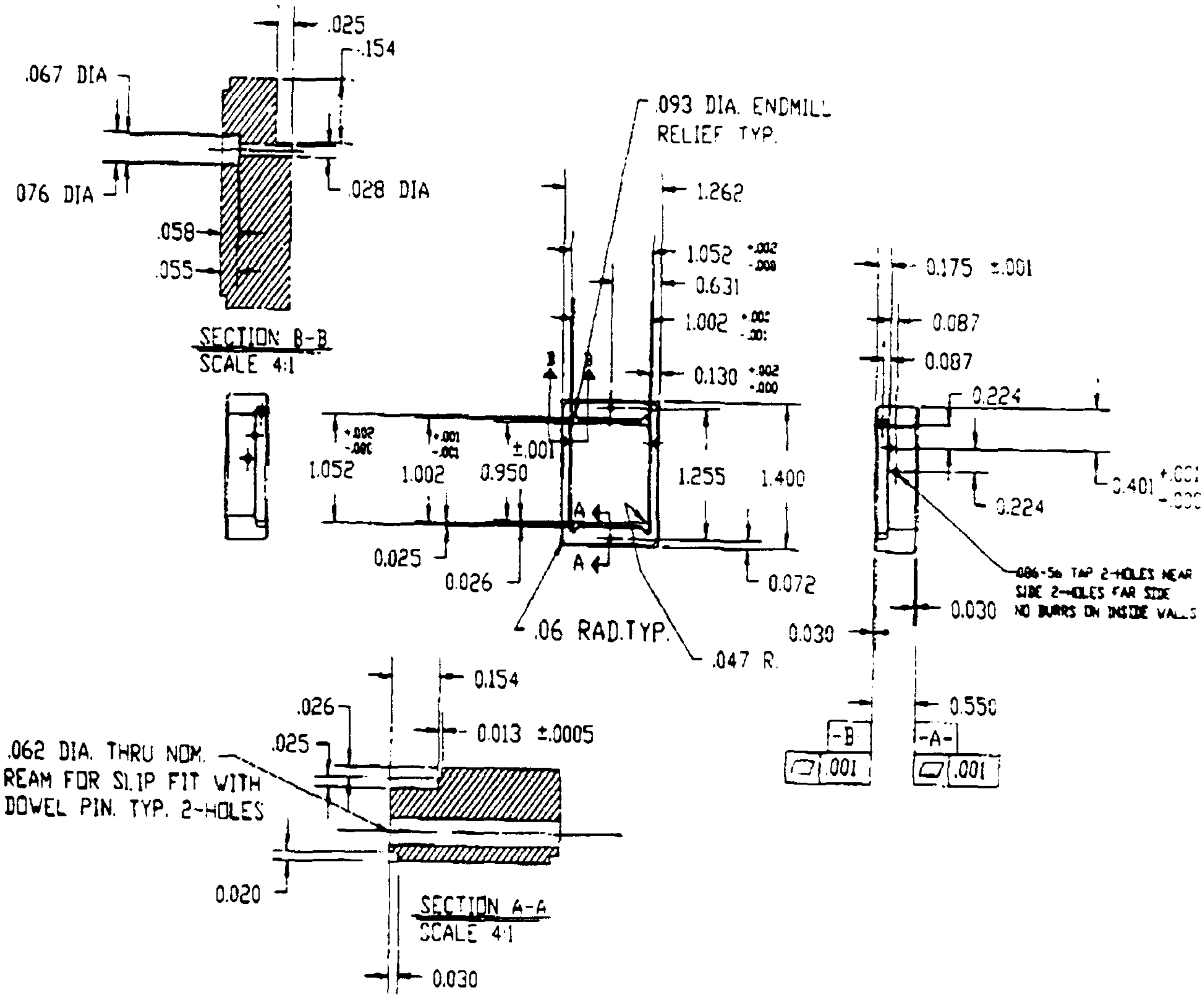


FIGURE 19. PACKAGE DIMENSIONS.

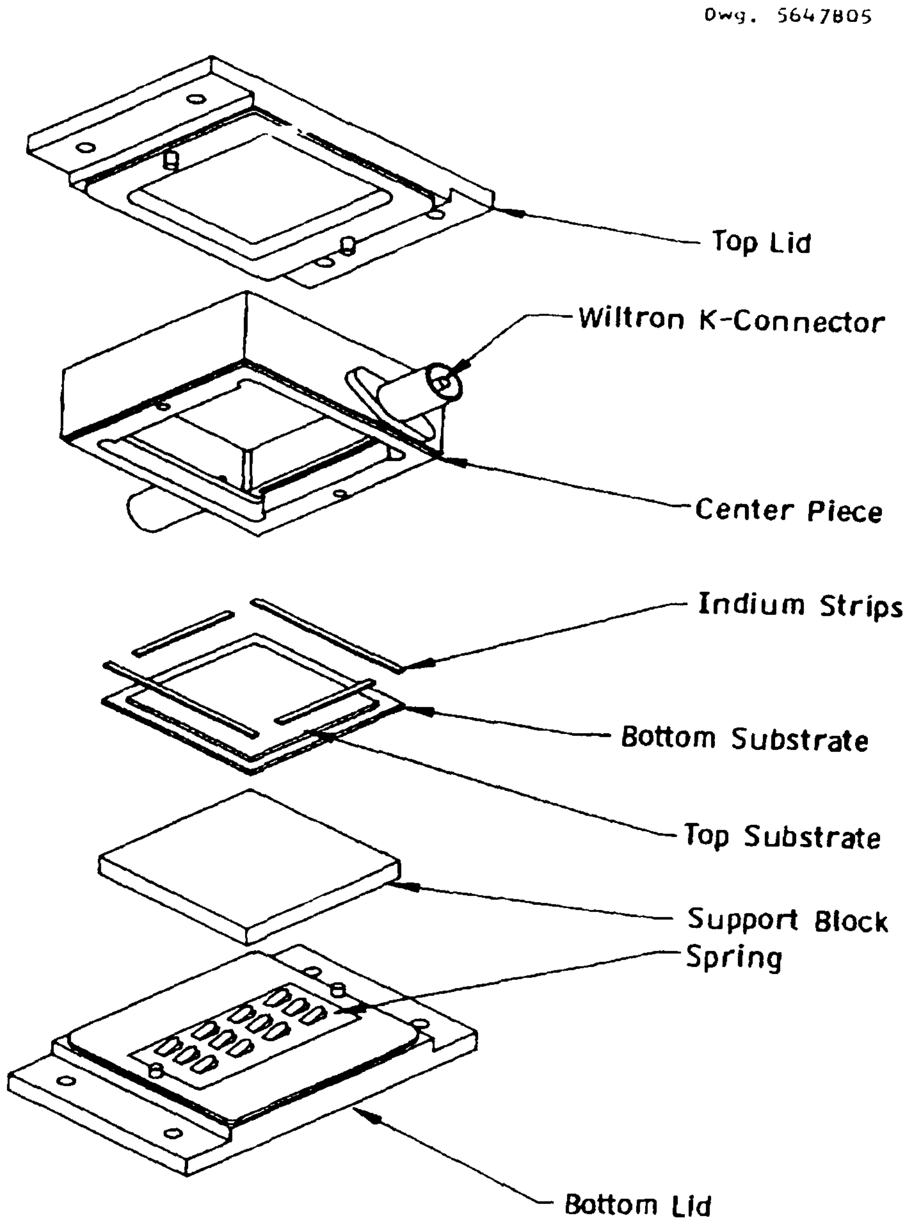
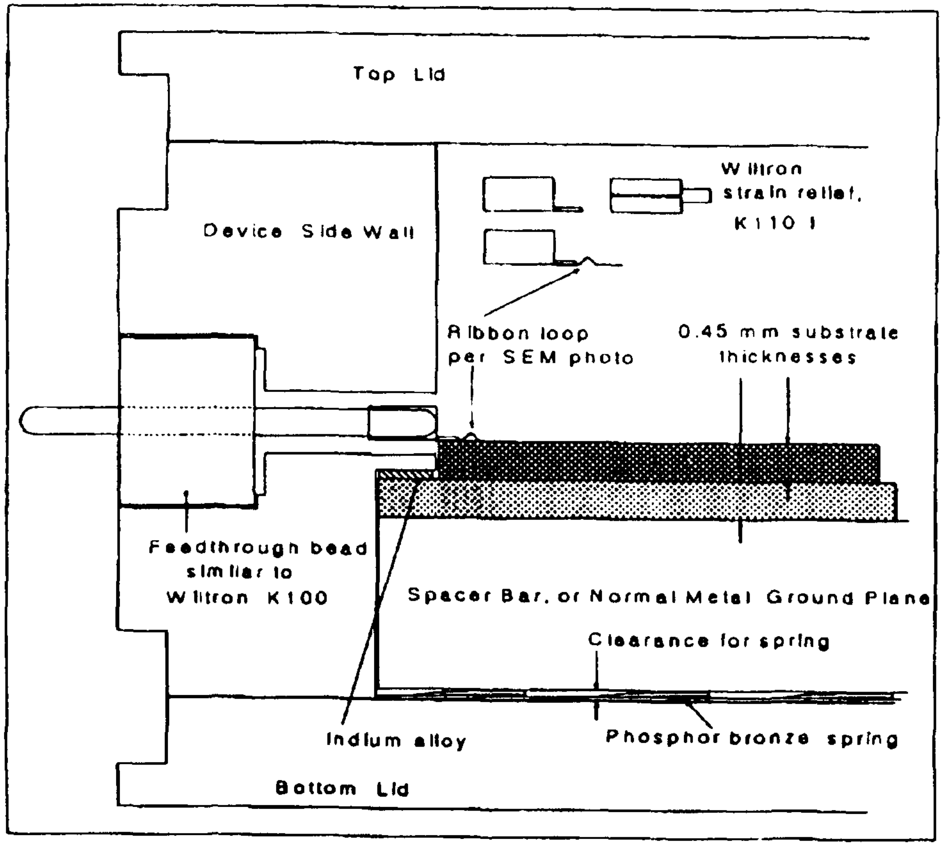


FIGURE 20. ISOMETRIC VIEW OF THE PACKAGE COMPONENTS AND HOW THEY FIT TOGETHER

PACKAGING ARRANGEMENT



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Science & Technology Center

FIGURE 21. DETAIL SHOWING THE COAXIAL GLASS BEAD AND SUBSTRATE ARRANGEMENT.

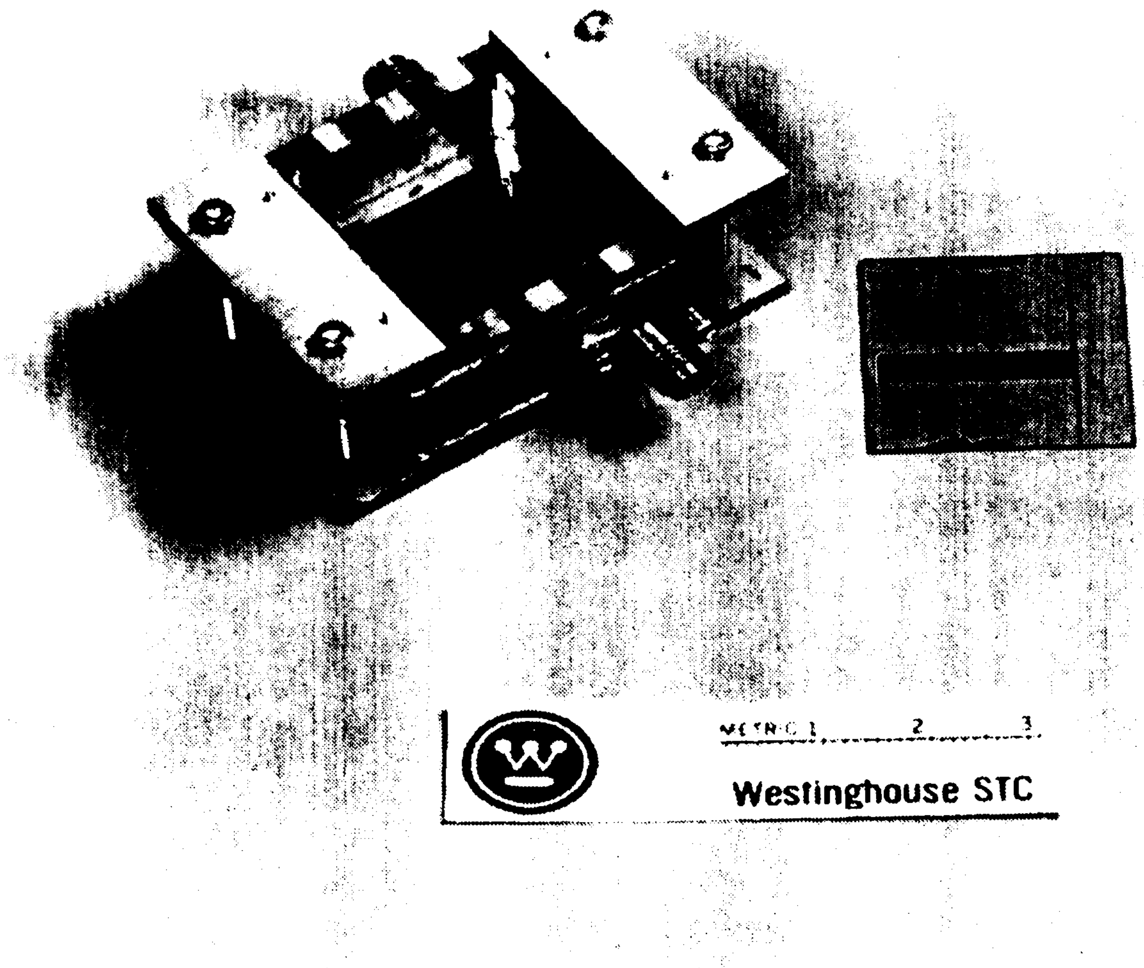

FIGURE 22. PHOTOGRAPH OF THE COMPLETED DEVICE

MEASUREMENT - Final Report

Single Radiator

The goal of the single radiator gain measurement was to measure the improvement in antenna gain that could be obtained by using an HTS matching network instead of a gold matching network. The experimental approach was to construct a monopole antenna with a gold matching network and a monopole antenna with an HTS matching network and to compare the two antenna gain measurements. For both the HTS and gold matching networks a single stub matching network was used. Because the conductivity of gold is significantly less than that of gold the Touchstone designed single stub matching networks were not identical. In both cases the matching networks were designed to maximize $|S_{21}|^2$ and minimize $|S_{11}|^2$.

The dielectric substrate thickness for the microstrip was 20 mils for the gold matching network and 17 mils for the HTS matching network. During the course of this work the manufacturer's standard thickness for the $LaAlO_3$ substrates changed from 17 mils to 20 mils. The results of the Touchstone optimized design for the 20 mils thick dielectric substrate were not changed in terms of maximized $|S_{21}|^2$ and minimized $|S_{11}|^2$ from the Touchstone optimized design for the 17 mils thick dielectric substrate. Table 2 lists the design parameters for the HTS and the gold matching networks.

The primary interest in the single monopole antennas was to measure the improvement of the HTS matching network relative to the gold matching network. The most direct means of determining the difference between the HTS matching network and the gold matching network was to make an S_{21} measurement with the monopole antenna attached to either the gold or HTS matching network operating in the receive mode and use another antenna operating in the transmit mode. The test fixture is shown schematically in figure 23. A comparatively long monopole, 7.6 cm, was anchored flush at the edge of the antenna ground plane. It was used as the transmit antenna. It radiated power to the receive antenna (the monopole under test), which was matched with either an HTS or a gold matching network.

In both cases, the matching network was cooled by immersing the matching network housing completely in liquid nitrogen contained in a Dewar. Cold

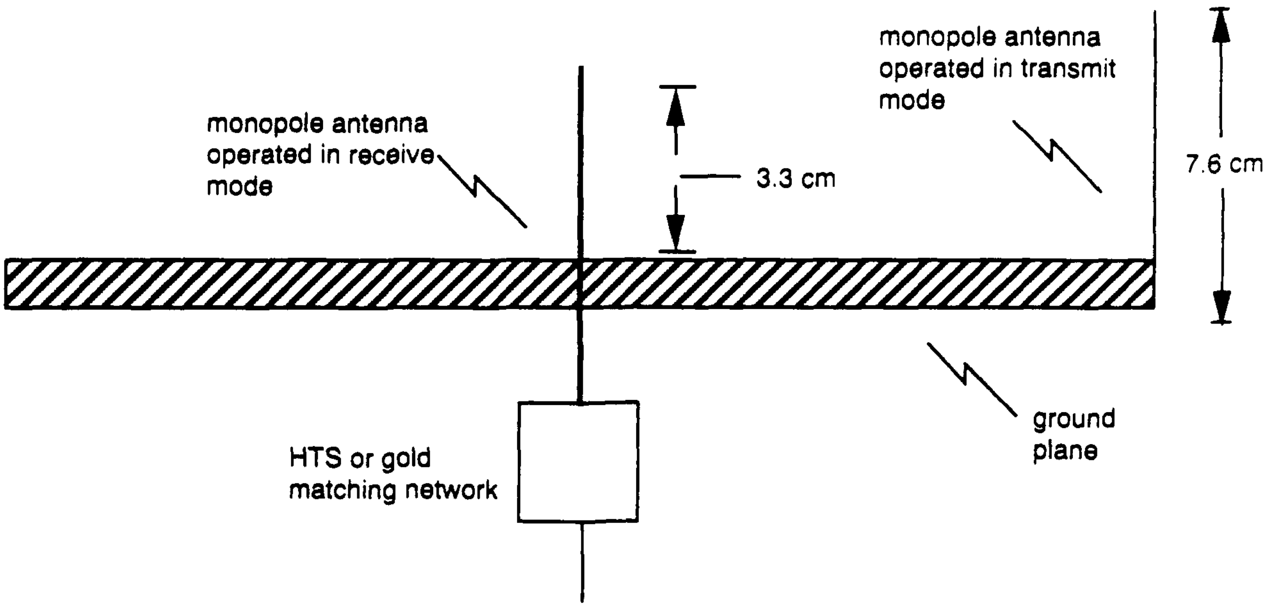

FIGURE 23 SCHEMATIC OF THE TEST FIXTURE USED TO MEASURE THE HTS AND GOLD MATCHING NETWORKS. THE DIFFERENCE IN MEASURED S21 IS DUE TO THE DIFFERENCES BETWEEN THE HTS AND GOLD MATCHING NETWORKS.

fingers attached to the matching network housing increased the heat transfer to the liquid nitrogen in the Dewar. Figure 24 is a photograph of the actual test fixture. The absorber leaning against the ANA was used to minimize reflection from the HP 8510A ANA. Numerous measurements showed that the S parameter data was highly repeatable even after the test fixture was repositioned.

The following data were obtained for the HTS and gold matched monopoles respectively:

HTS at 769 MHz

S_{12} = 29.03 dB, S_{11} = 4.5 dB, S_{22} = 4.76 dB

Gold at 769 MHz

S_{12} = 31.10 dB, S_{11} = 4.96 dB, S_{22} = 4.64 dB

Therefore, the HTS matched monopole had about 2 dB more gain than the gold matched monopole. Since both matching network return losses or reflected powers (S_{11}) were about equal, we attributed the difference in gain to the lower loss in the HTS matching network. The difference in the transmit monopole return losses (S_{22}) is due to measurement uncertainty, since the same monopoles were used.

In order to determine the absolute loss through the gold matching network, we made gain measurements on a UHF antenna range. The measurement test set-up is shown schematically in figure 25. Figure 25 illustrates a standard method for measuring antenna gain. The antenna under test (in our case the gold matched monopole antenna) was placed on the measurement tower. A transmit antenna radiated towards the test antenna. The receiver (SA 1742) received the power (at a single frequency, as opposed to the S_{12} method on a HP8510A), whose level was plotted on the recorder (SA 1520). If desired, the tower could be rotated to obtain an antenna pattern. The initial step was to determine the frequency at which the received power peaked. The 7.6 cm monopole antenna was used as the transmit antenna. The received power peaked at 774 MHz. Then we replaced the monopole antenna with a standard gain horn (Nurad 7RH) and connected a 10 dB attenuator in series with it. The power level corresponds to the gain horn's gain (read from a gain measured curve for the standard gain horn supplied by Nurad) minus the 10

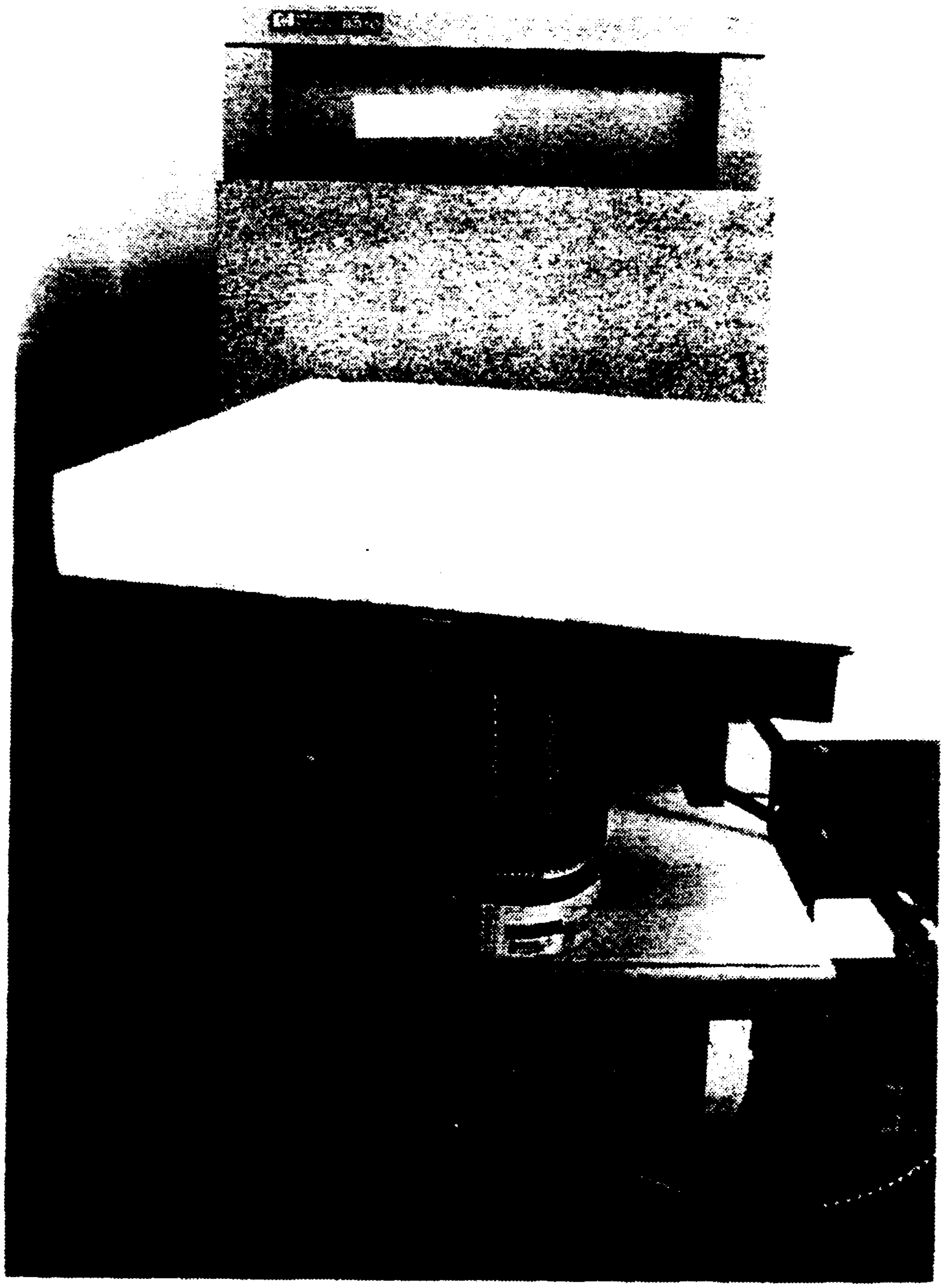

FIGURE 24. PHOTOGRAPH OF THE TEST FIXTURE USED TO DETERMINE THE LOSS THROUGH THE HTS AND GOLD MATCHING NETWORKS.

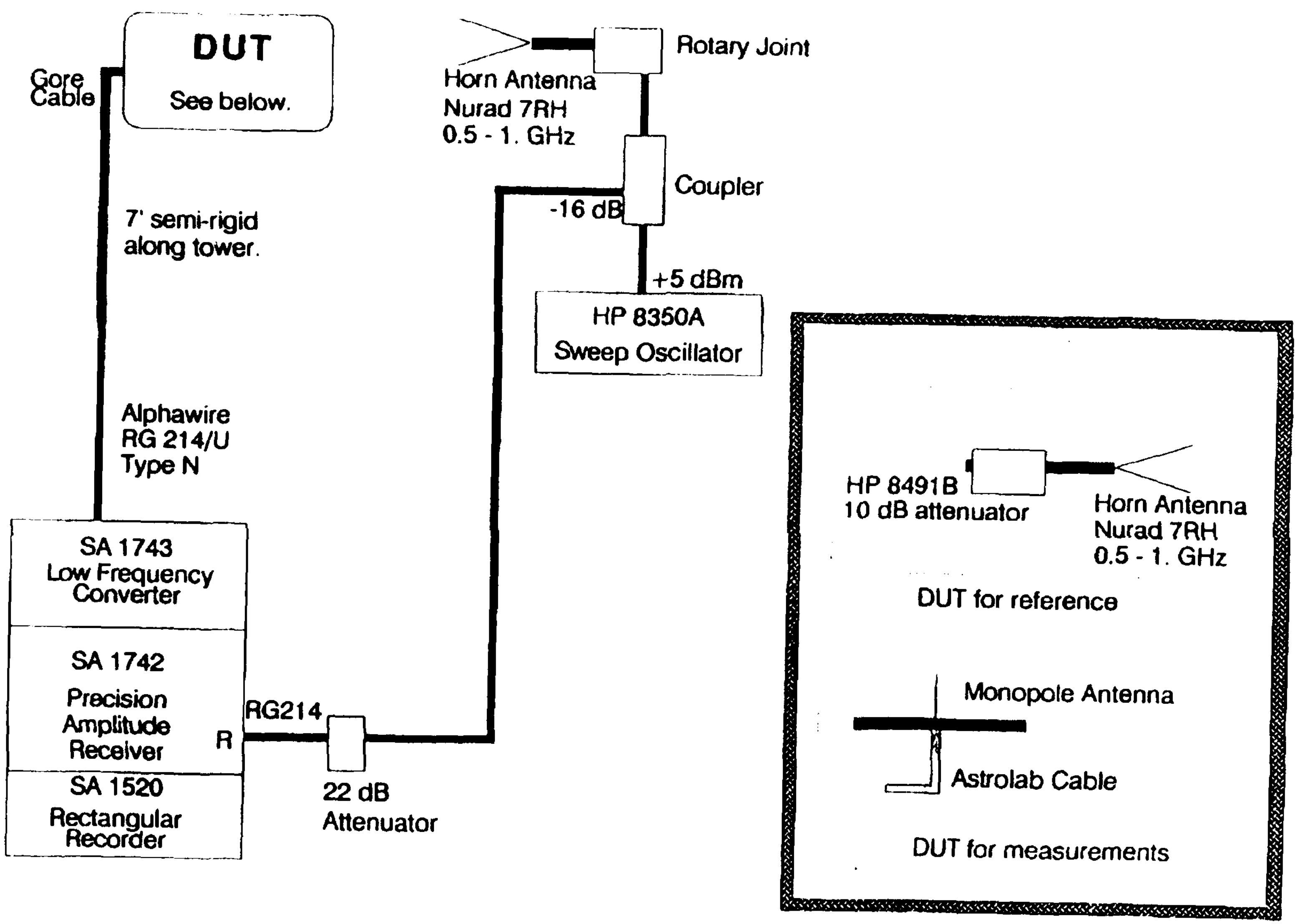

FIGURE 25. TEST FIXTURE FOR ANTENNA GAIN MEASUREMENTS.

dB of the attenuator. From this we determined the 0 dBi level on the monopole antenna gain plot.

The measured gain of the monopole antenna at phi = 0 degrees and theta = 90 degrees was approximately -9 dBi. This is a rough number only, because it is difficult to measure a low directivity antenna such as an electrically short monopole. ESP predicts a gain of -1 dBi for this monopole antenna. Therefore, the measured loss through the liquid nitrogen cooled matching network is approximately 8 dB. Touchstone predicted a 7 dB loss.

Antenna Array

As was mentioned previously, due to budget cutbacks, we were forced to build a two element monopole array rather than a four element monopole array. An array tuning circuit was used to induce the correct phases and amplitudes for the two element array. Two couplers were connected in series with each monopole matching network in order to sample the reflected and incident power. The reflected power was sampled by an HP 8755C scaler network analyzer. The reference channel power was generated by sampling the power incident on the matching network. Attenuators were used to adjust the desired power level in the individual radiators. Using an ANA we characterized the components of the array tuning circuit. The phase shifters and attenuators were measured for a angle of settings. Using the components' individual characteristics, we adjusted the phase shifters and attenuators for the proper array illumination. Measuring the assembled circuit, we found that the adjustments were accurate to within about 4 degrees and a .5 dB of the desired illumination for the superdirective and uniform endfire cases.

Previous sections have discussed the improvements in HTS material processing technology that occurred during the time period covered by this report. However, HTS material processing is still in the experimental stage. One of the HTS matching networks built for the two element array failed completely (each monopole antenna in the array was separately matched with an HTS matching network. Thus the two element array had two matching networks). In order to test the two element array the failed HTS two element array matching network was replaced with the HTS matching network from the single monopole antenna. One problem with using the HTS matching network from the single monopole antenna in a two element array is that the impedance to be matched differed substantially. A second problem with using the HTS matching network from the single monopole antenna is that HTS material tends to degrade (have more loss) with repeated temperature cycling and with exposure to humidity.

In order to produce an acceptable far field radiation pattern with the improvised HTS matching network the two monopoles were length tuned. Because of the differences in the two matching networks there was a significant difference in the lengths of the two monopoles; 2.11 cm and 4.37 cm. The attenuation in the second monopole was increased approximately 4 dB to compensate for the difference in monopole length. The phase difference between the two feeds for the two radiators was set at 142 degrees. The far field radiation pattern is shown in figure 26.

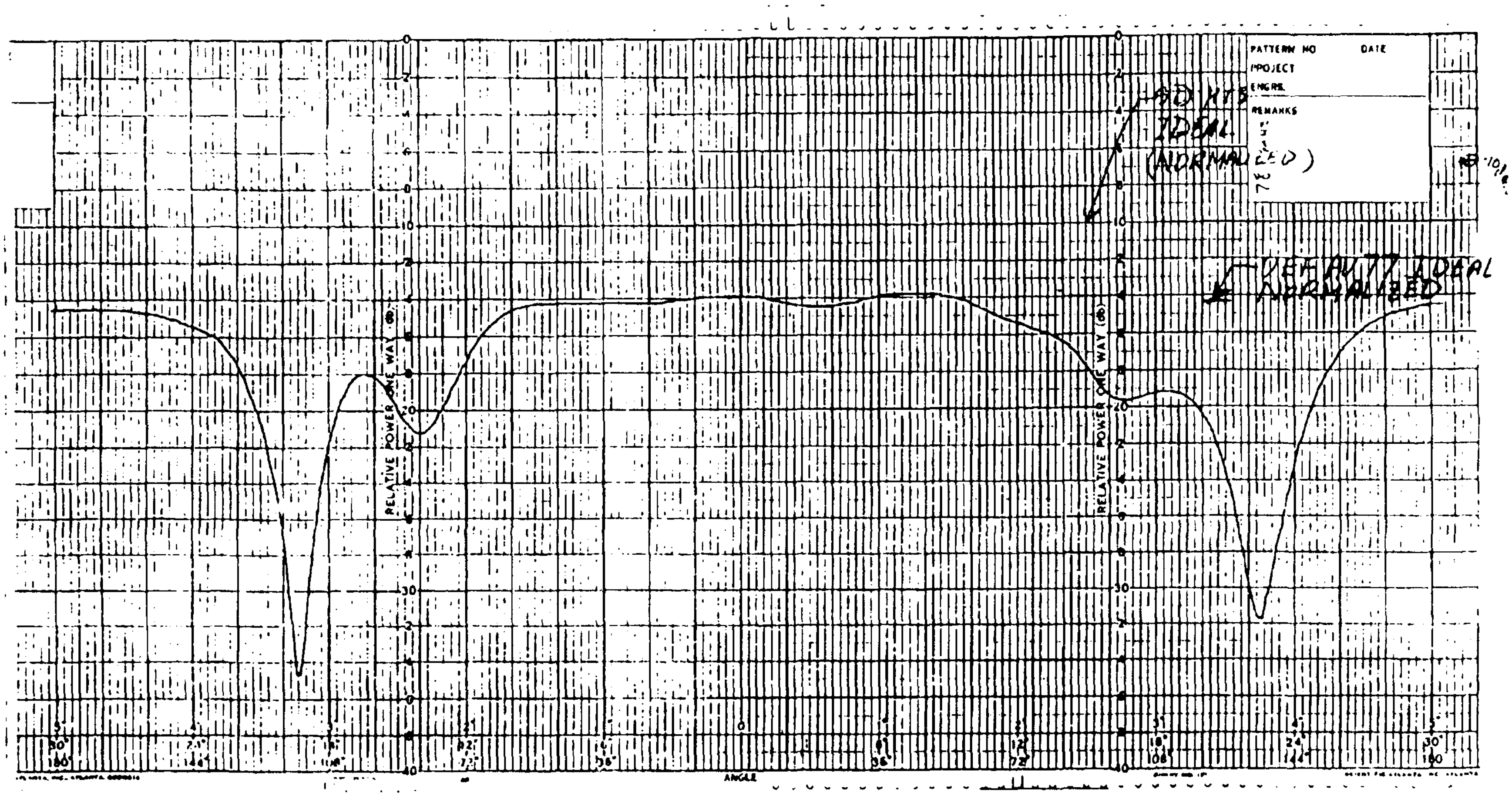

FIGURE 26. PLOT OF THE MEASURED E-THETA COMPONENT OF THE TWO ELEMENT ARRAY AS A FUNCTION OF THETA.

HTS SUMMARY

During the course of this work we built and tested UHF matched electrically small single element monopole antenna, a gold matched electrically small single element monopole antenna, and an HTS matched electrically small two element monopole super directive array. In order to accomplish the above tasks, significant progress had to be made in the film growth and fabrication of YBCO devices.

At the conclusion of this study the film growth and fabrication of HTS devices was still in the experimental stage, although substantial progress had been made. Wafer fabrication had progressed from 1 inch diameter wafers to 2 inch diameter wafers. At the beginning of the program only single sided YBCO films were grown. At the end of the program double sided YBCO films were grown. One problem that remained at the conclusion of the investigation was the variation of R_s from wafer to wafer. The average R_s varied from 250 to 1500 times lower than copper at 800 MHz and 77 k from one wafer to another. In addition one of the HTS matching networks built for the two element array failed completely.

S_{12} measurements of the HTS matched single element monopole antenna and the gold matched single element monopole antenna showed that the gold matching network had 2 dB more loss than the HTS matching network. One feature of the HTS matched single element monopole antenna was that it had a substantially narrower bandwidth than the gold matched single element monopole antenna.

A five element array was initially planned for demonstration of the super directive array concept. Funding restrictions during the fabrication phase change the array definition to a two element array. The HTS matched two element array produced a very acceptable far field radiation pattern. One of the HTS matching networks designed for the two element array failed during initial testing which forced us to use a matching network designed for the single element array. The monopole antennas in the array were clipped in order to provide an acceptable match and produce an acceptable pattern.

One possible application of HTS matching networks is in linear arrays. For example if HTS matching networks are used in place of silver or copper matching networks in a 6 or 8 element monopole array substantial increases in radiation efficiency are possible.

The improvement in efficiency if HTS matching networks were used instead of copper or silver matching networks in a 6 or an 8 electrically small monopole element array was calculated using ESP, an Ohio State University moment method code. Efficiency was defined at the terminals of the matching network as

$$\text{Efficiency} = P_{rad}/(P_{rad} + P_{loss})$$

where P_{rad} was the power radiated by the antenna and P_{loss} was the power dissipated in the antenna array including losses in the matching network.

For a 6 element electrically small monopole array the frequency of operation was 800 MHz. The element spacing was .131 m (= .35 wavelengths at 800 MHz). The monopole height was 6 cm (= .16 wavelengths at 800 MHz). Table 3 lists the impedances of the 6 element array.

Table 3 - Input impedance of the elements of the six element array.

Element Number	Input Impedance
1	15.407 - j349.8 ohms
2	6.346 - j330.8 ohms
3	4.621 - j328.2 ohms
4	8.898 - j332.7 ohms
5	13.349 - j343.4 ohms
6	6.532 - j361.4 ohms

The matching networks were parallel single stub tuners. The efficiency of the copper matched 6 element array was 22.5 %. The efficiency of the HTS matched 6 element array was 74.0 %. The array length was 78.72 cm.

For the 8 electrically small monopole element array the frequency of operation was also 800 MHz. The element spacing was .1499 m (= .4 wavelengths at 800 MHz). The monopole height was 7 cm (= .187 wavelengths at 800 MHz). Table 4 lists the impedances of the 8 element array.

Table 4 - Input impedance of the elements of the eight element array.

Element Number	Input Impedance
1	10.713 - j336.6
2	10.702 - j303.6
3	8.645 - j312.2
4	10.107 - j319.8
5	13.085 - j322.1
6	13.203 - j320.7
7	9.871 - j321.3
8	2.846 - j352.5

The matching networks were parallel single stub tuners. The efficiency of the copper matched 8 element array was 23.2%. The efficiency of the HTS matched 8 element array was 96.2%. The array length was 1.1992 m.

The major source of the loss in the arrays was the vast disparity between the antenna impedance and the 50 ohm transmission line impedance. Because of this disparity, the standing wave ratio in the matching networks (both HTS and conventional metal) was quite high. The losses in the HTS matching networks were much lower than the losses in the conventional metal matching networks because the conductivity of the HTS material (approximately 10^{11}) was so much larger than the conductivity of the conventional metals (approximately 10^{7}).

Conventional cryocoolers such as split Sterling or Gifford-McMahan are available to provide cooling for HTS devices. In addition MMR Technologies miniature Joule_Thompson coolers offer considerable improvement in weight, volume, and manufacturing cost at comparable thermal efficiencies and heat flux over conventional cryocoolers.

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